The US Belle II Collaboration

Brookhaven National Lab
Carnegie Mellon University
University of Cincinnati
Duke University
University of Florida
University of Hawai'i
Iowa State University
Indiana University
University of Louisville
Luther College
University of Mississippi
Pacific Northwest National Lab
University of Pittsburgh
University of South Alabama
University of South Carolina
Virginia Tech
Wayne State University

Flavor physics as a tool for discovery at Belle II

Jake Bennett (University of Mississippi) on behalf of US Belle II

P5 town hall - March 23, 2023

Belle II snowmass executive summary: https://arxiv.org/abs/2203.10203
Belle II white paper: https://arxiv.org/abs/2207.06307
RPPF frontier summary: https://arxiv.org/abs/2301.06581 (section 1.4.8)
"Belle II Vision in High Energy Physics", submitted to the National Academy of Sciences

Captions

The hunt for New Physics

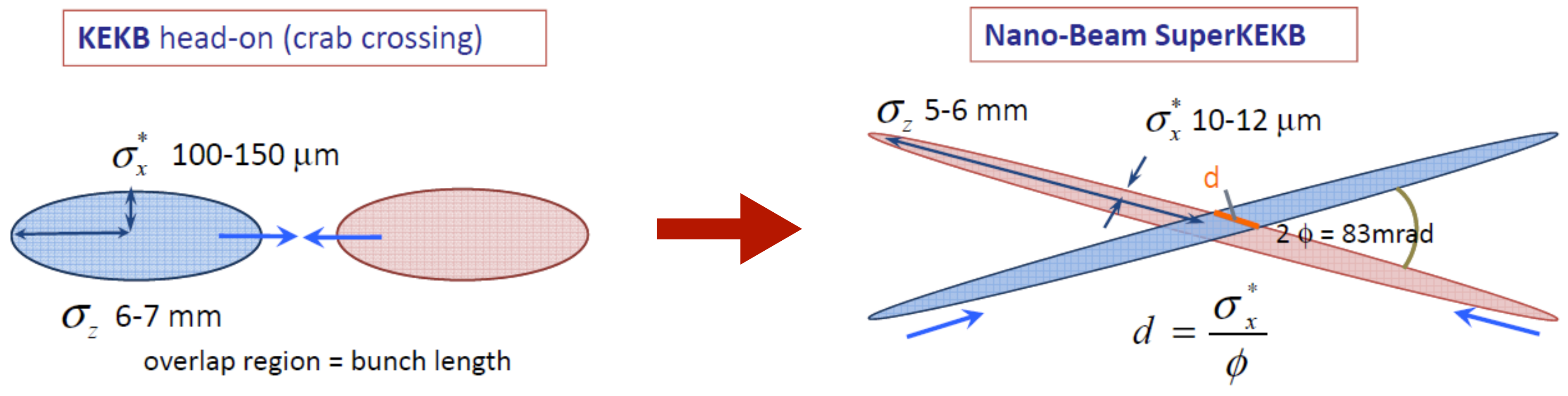
Unique discovery potential at Belle II

- Mapping and understanding physics Beyond the Standard Model (BSM) will require the full range of the Rare Processes and Precision Measurements Frontier (RPPF) and Energy Frontier experiments
  - Complementarity and combined potential for uncovering NP is major strength of US HEP program
  - Absence of BSM discoveries at LHC emphasizes need for RPPF experiments
  - First signs of NP may be seen in high-precision measurements of suppressed processes
- B-factories, Belle @ KEKB and BaBar @ PEPII played crucial roles in advancing knowledge
  - Large samples of B mesons, charm hadrons, tau leptons, and low-multiplicity events
  - Discovery of CPV in the B system (*recognized by 2008 Nobel Prize*)
  - Published almost 1200 papers, still publishing more than 10 years after shutdown
- Belle II @ SuperKEKB are significant improvements over predecessors
  - Expected to record 50 ab^{-1}, two orders of magnitude more than BaBar and 50 times that of Belle
  - International team collaborating to optimize path for accessing SuperKEKB's full potential

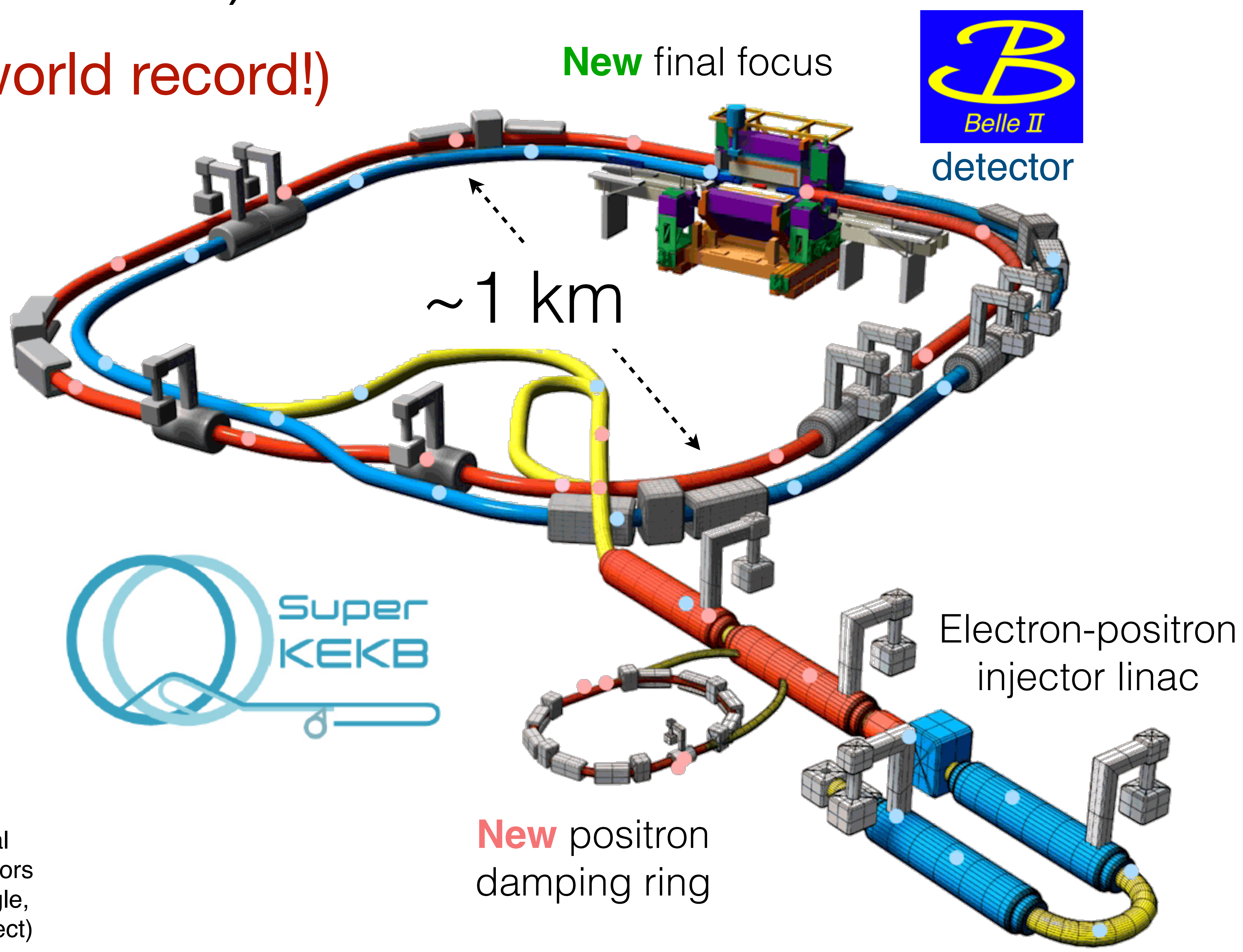
Captions

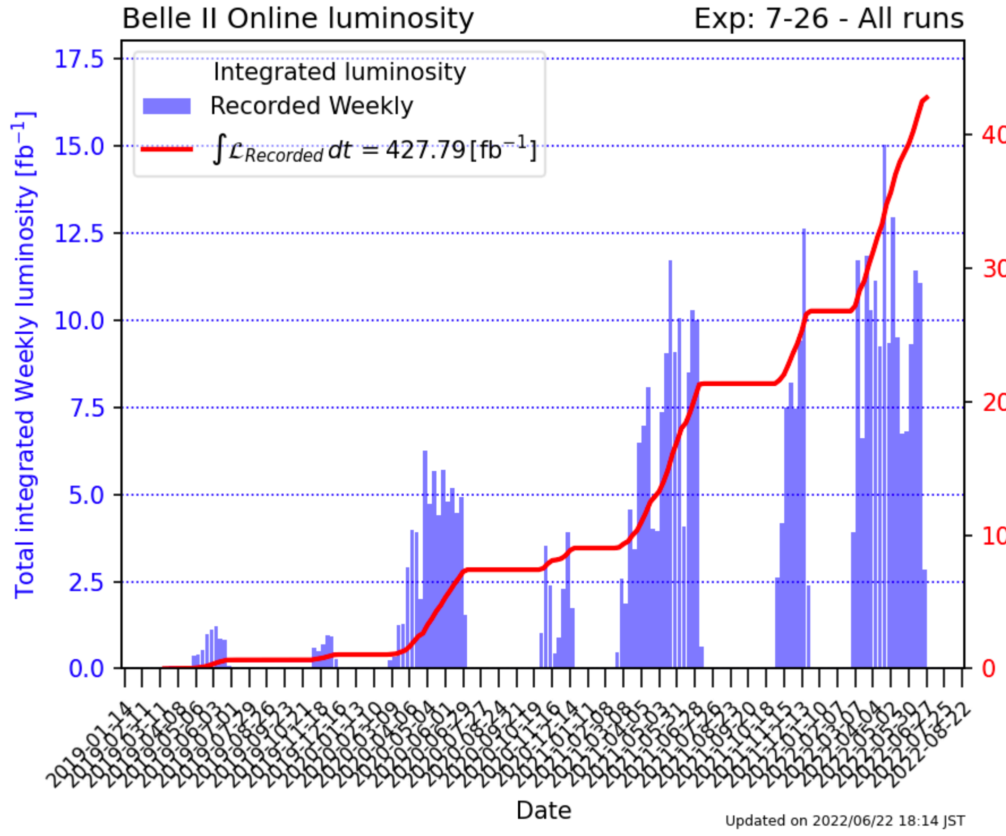
SuperKEKB

High-luminosity Super B factory



- Asymmetric electron-positron collider at $\Upsilon(4S)$
  - Target instantaneous luminosity: $\mathscr{L} = 6 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$ (30x KEKB)
  - Max instantaneous luminosity: $\mathscr{L} = 4.7 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (world record!)
- Nano-beam scheme
  - Increase beam current, squeeze beams at the IP, reduced beam energy asymmetry
  - Target beam height: 50 nm; current value: 300 nm
- Belle II @ SuperKEKB ran throughout the global pandemic





$$L = \frac{\gamma_\pm}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor

Beam current

Beam-Beam parameter

Geometrical reduction factors (crossing angle, hourglass effect)

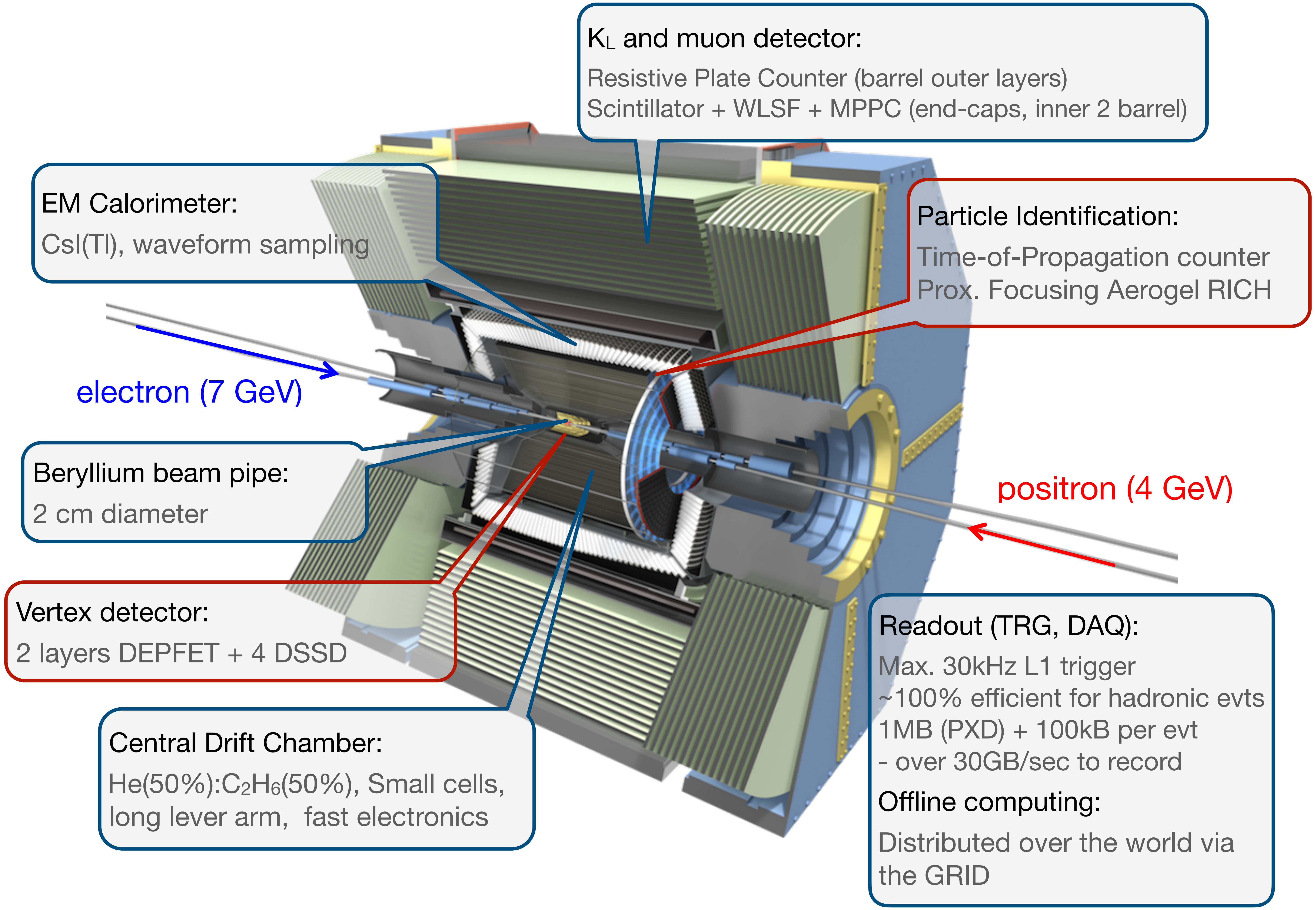
Beam aspect ratio at IP

Vertical beta function at IP

Captions

Belle II

Experiment @ SuperKEKB



$$c\bar{c},\ s\bar{s},\ d\bar{d},\ u\bar{u},\ \tau^+\tau^- \leftarrow e^+e^- \rightarrow \Upsilon(nS) \rightarrow B^{(*)}\bar{B}^{(*)}$$

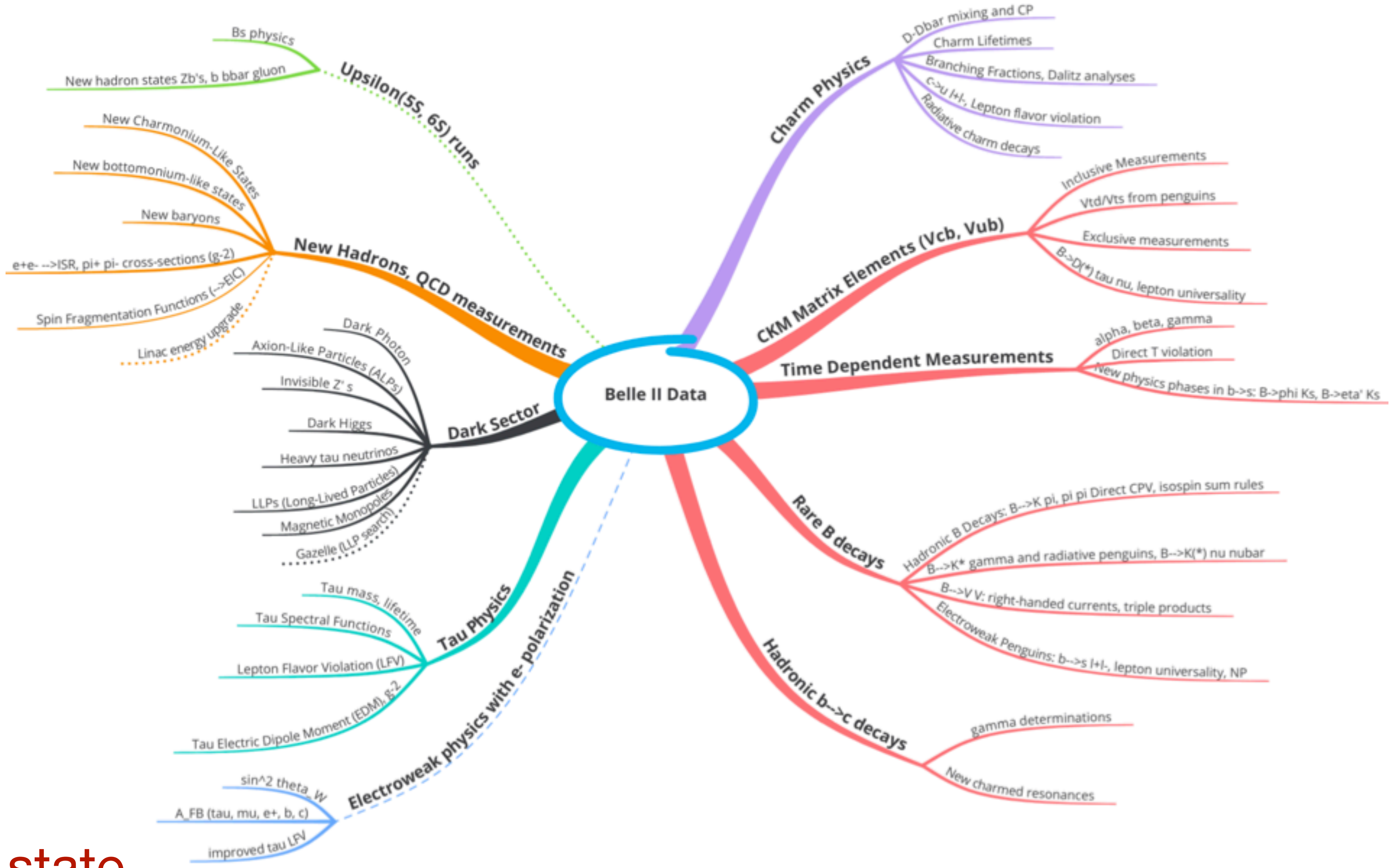
- Multipurpose detector designed to reconstruct all visible particles
  - Excellent vertexing - silicon pixels improve track impact parameter and vertex resolution by about a factor of two over Belle/BaBar
  - High-efficiency detection of neutrals $(\gamma,\ \pi^0,\ \eta,\ \eta',\ \ldots)$
  - High trigger efficiency, including for low multiplicity events
  - Reconstruction performance at least as good as Belle & BaBar
- US Belle II groups play leading roles in design, construction, and operation of detectors, computing, and physics
  - TOP and KLM: 5 year US effort costing $16M - operating well!
  - T1 GRID computing facility at BNL

Captions

Belle II
Experiment @ SuperKEKB

- Some benefits of the physics program at B factories:
  - Background levels generally low due to small multiplicity of final state particles, no pile-up
  - Reconstruction efficiencies flat across Dalitz plot and as a function of decay time
  - Well-known initial state and hermetic detector allow for fully-inclusive searches and searches for new particles via missing mass
  - Flavor-tagged, time-dependent observables measurable at threshold where boosted $B\bar{B}$ pairs produced in quantum coherent state
  - Inclusive decays and absolute branching fraction measurements that may be impractical at hadron machines

The Belle II Physics Program
Goal: uncover new physics beyond the SM



Captions

Per ab^{-1} (events $\times\, 10^9$): 1.1 $B\bar{B}$, 1.3 $c\bar{c}$, 2.1 $q\bar{q}$, 0.9 $\tau^+\tau^-$

Recent results

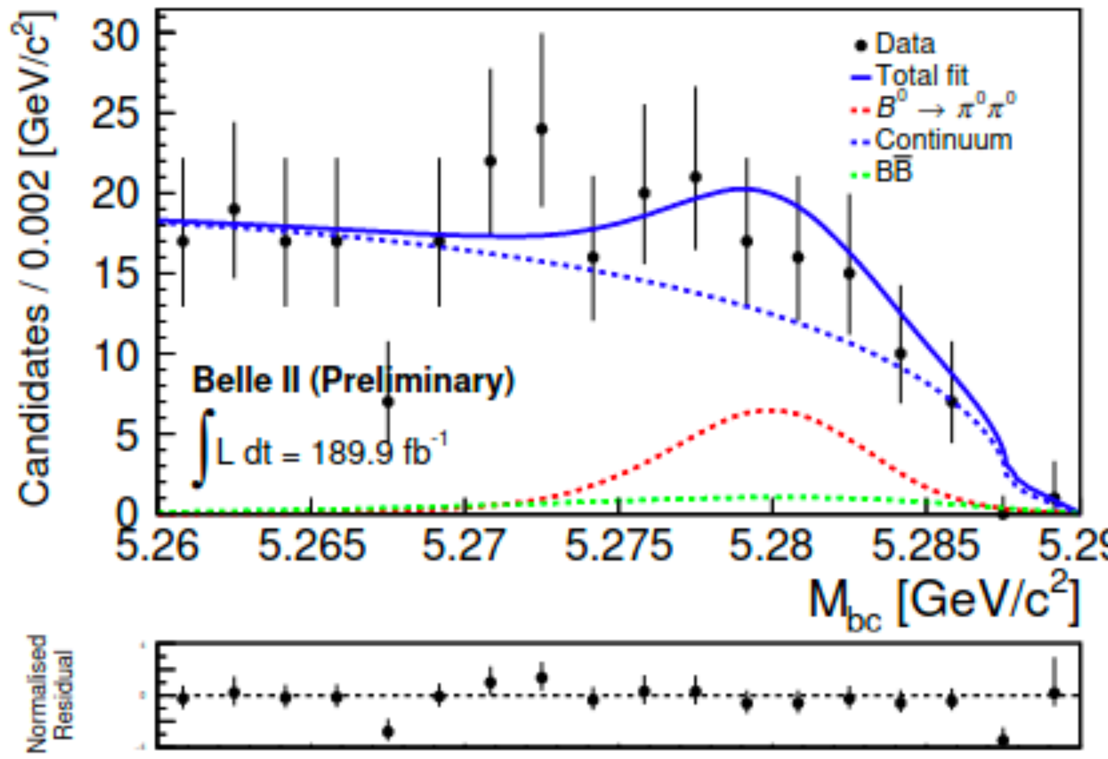
Just a flavor…

Branching fraction and CP asymmetry of $B \to \pi^0\pi^0$

$$A_{CP} = 0.14 \pm 0.46 \pm 0.07$$
$$\mathcal{B} = (1.27 \pm 0.25 \pm 0.17) \times 10^{-6}$$

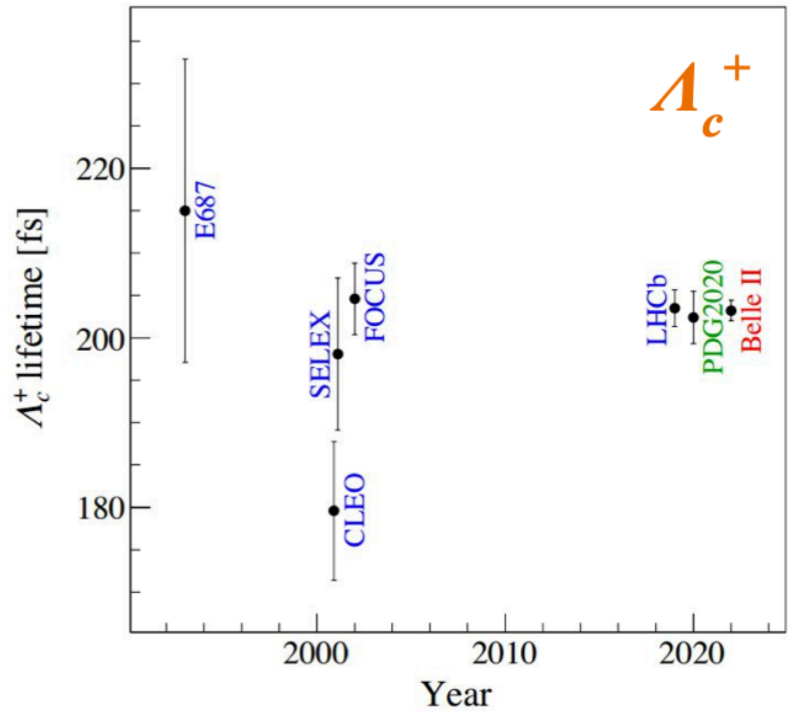
Close to Belle precision with only ~1/4 of the dataset

Belle II can handle all-neutral final states!



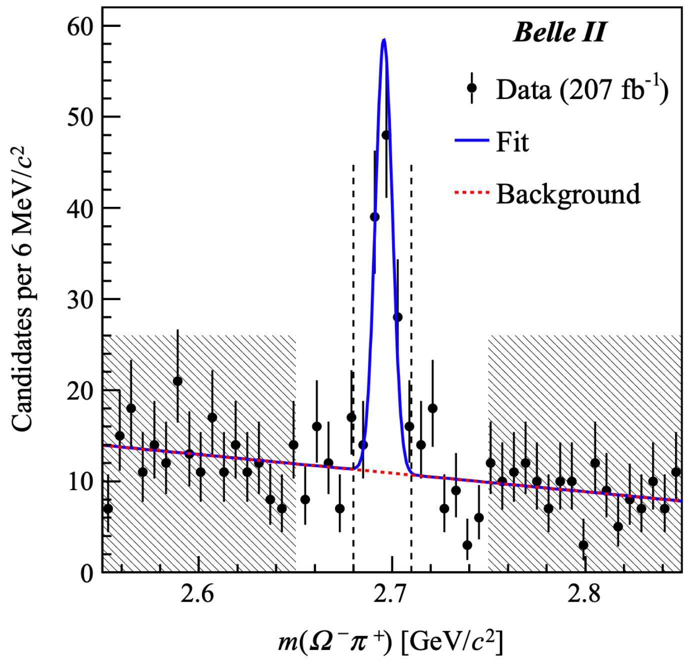
To be submitted to PRD

World's most precise lifetime measurements of the Λ_c^+, D^0 and D^+, new measurement for Ω_c^0



Few per-mil accuracy establishes excellent detector performance

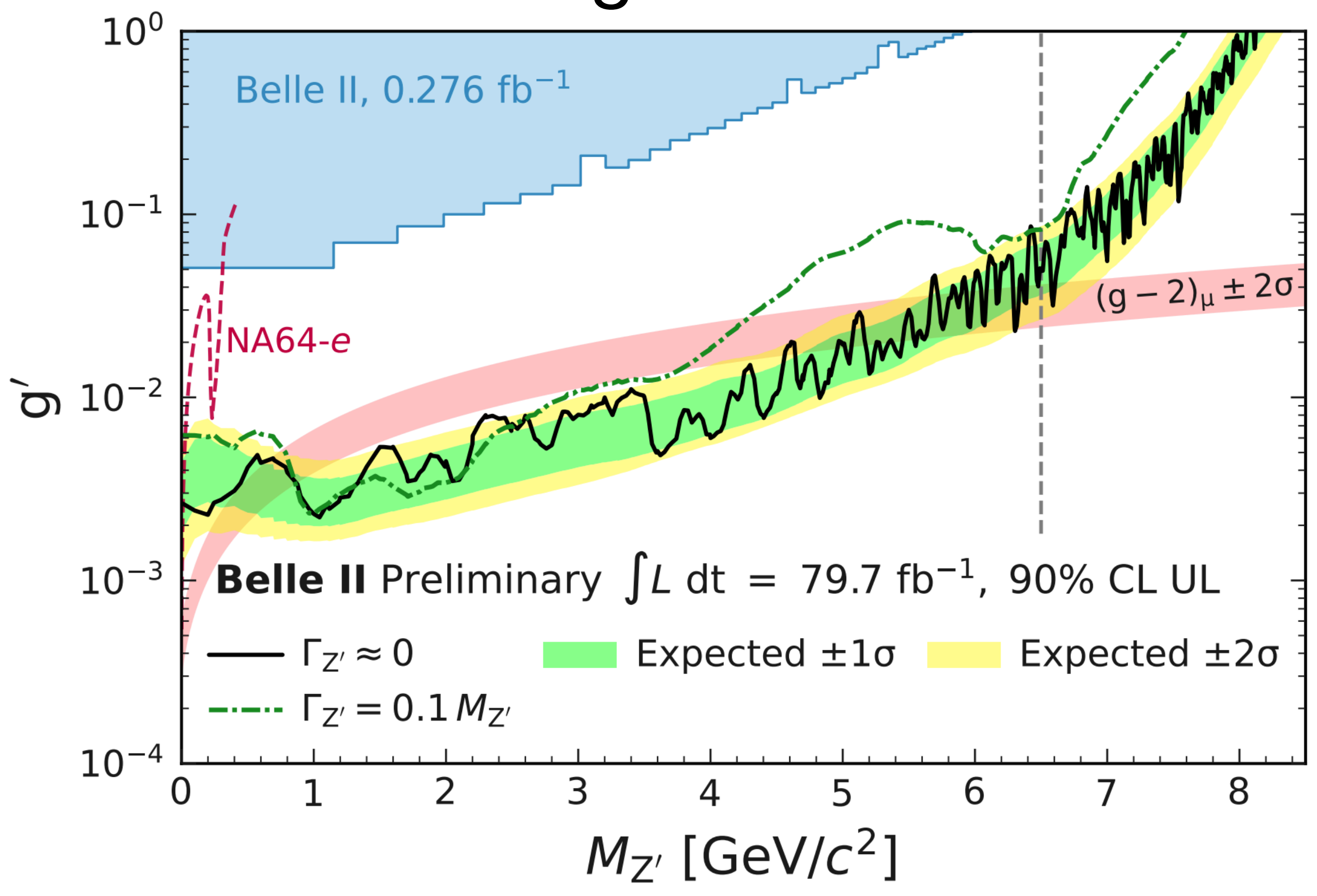
World-leading results with existing datasets



PRL 127 211801 (2021), PRL 130 071802 (2023), arxiv:2208.08573 (accepted PRDL)

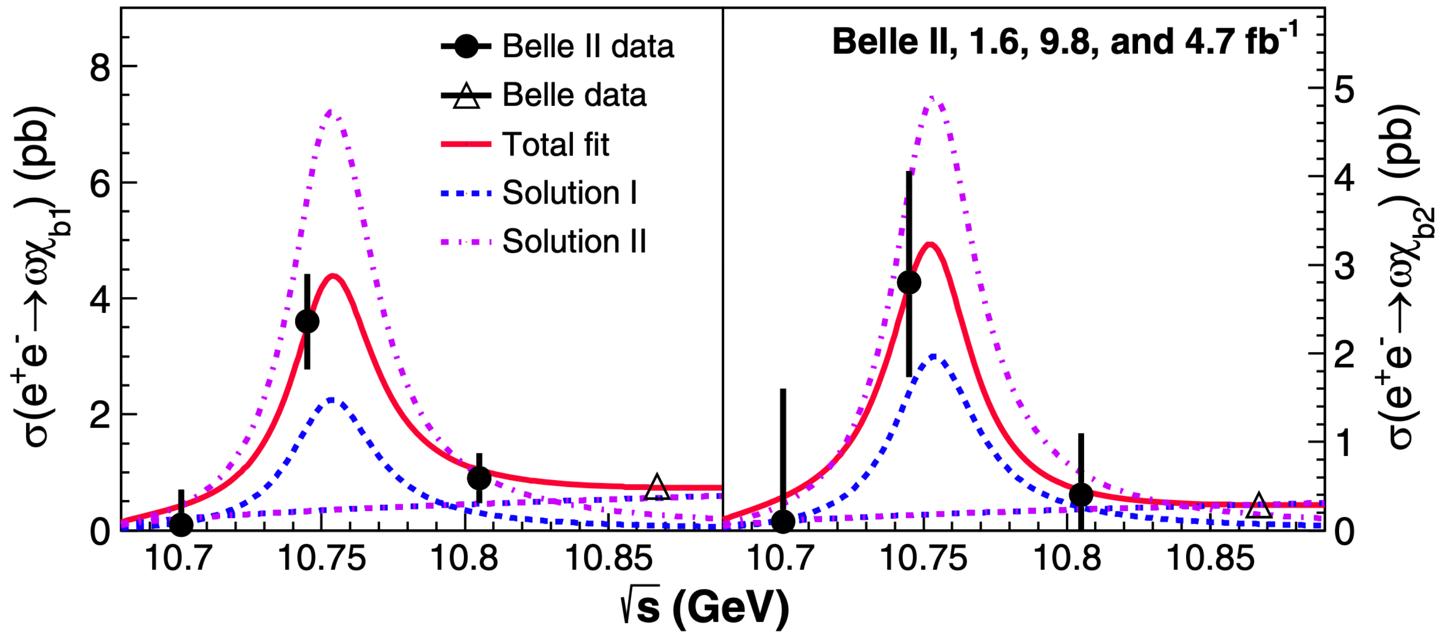
Search for invisible Z' with missing energy

Most stringent limits to date



arxiv:2212.03066 (Submitted to PRL)

Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ and search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV



PRL 130 091902 (2023)

Hadron spectroscopy with unique datasets

Study of exotics (see backups)

Captions

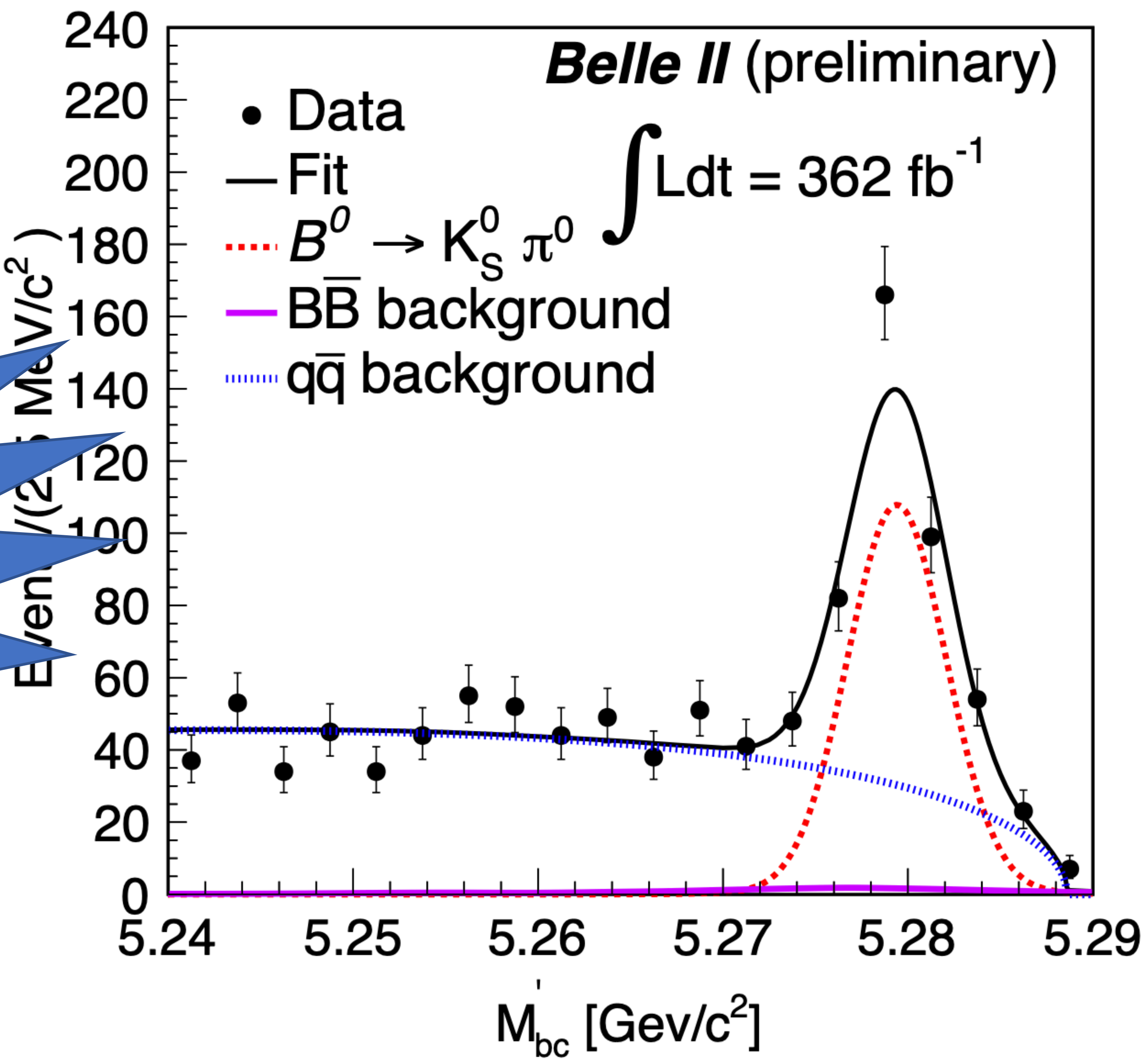
More at https://confluence.desy.de/display/BI/Journal+Publications

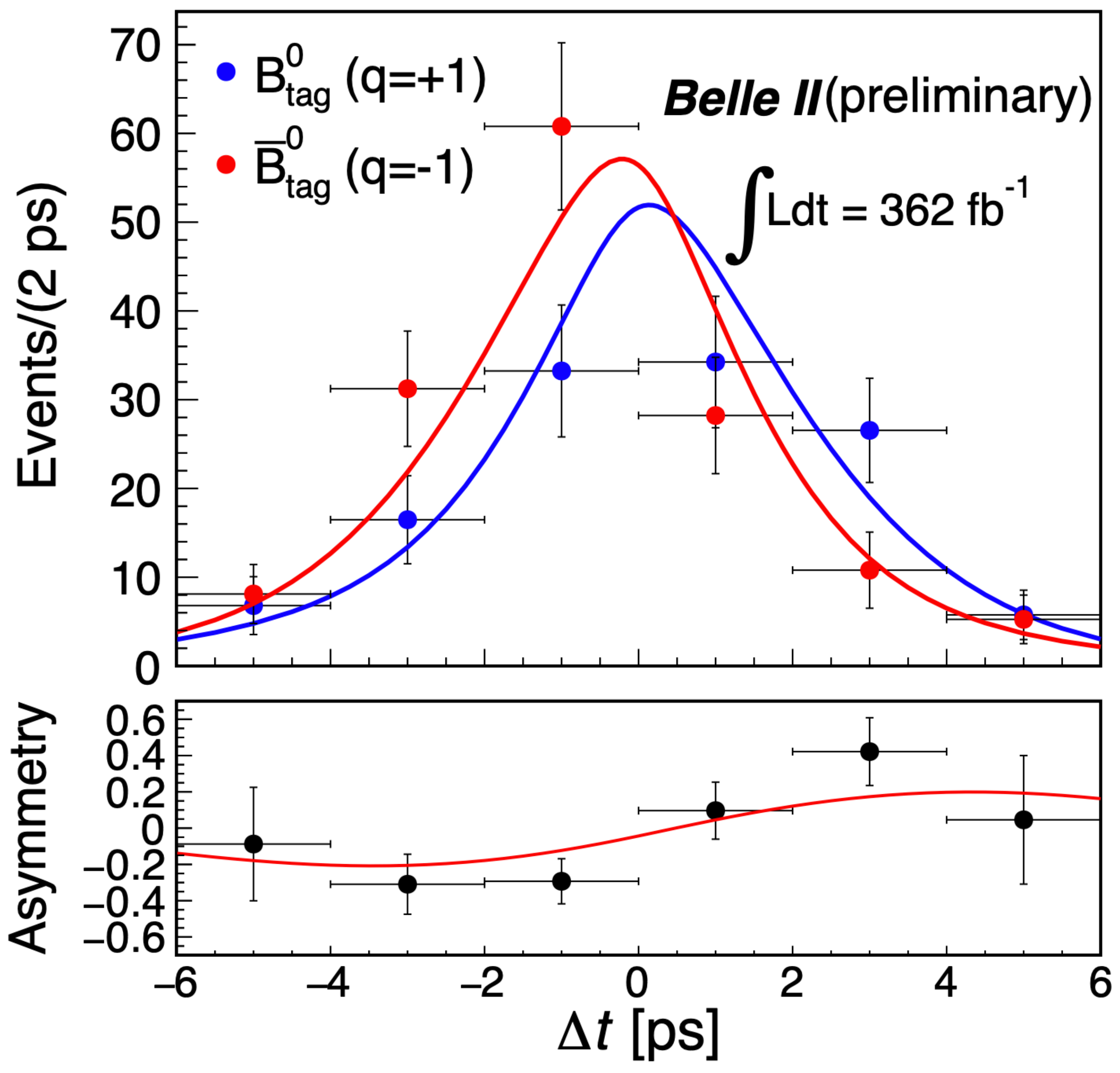
Recent results

Just a flavor…

Time-dependent CP asymmetries in $B \to K_S^0 \pi^0$

New, impactful results are being revealed at Moriond 2023!





Competitive with world's best results with much lower luminosity

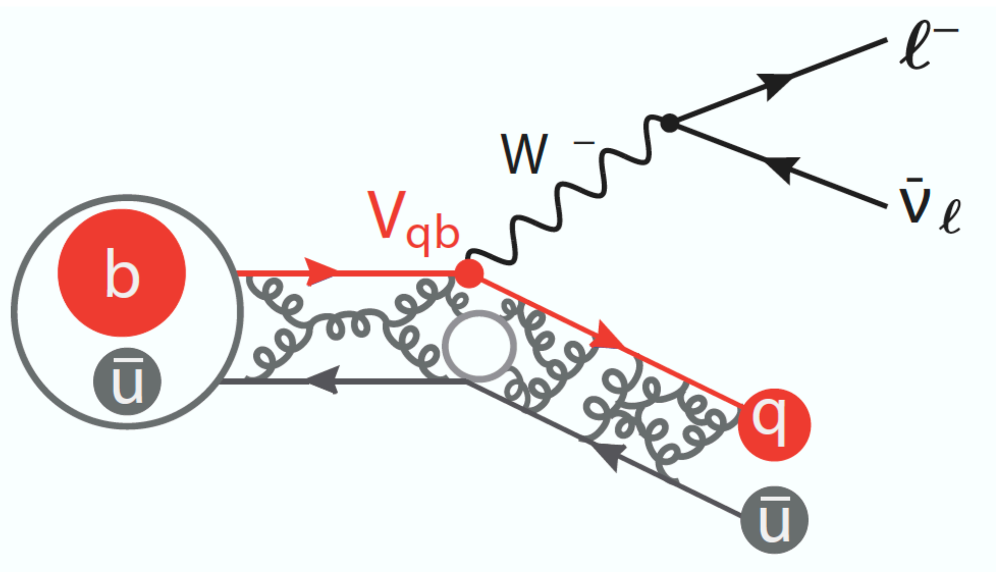
$$A_{CP} = 0.04 \pm 0.15 \pm 0.05$$
$$S_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04$$

Captions

More at https://confluence.desy.de/display/BI/Journal+Publications

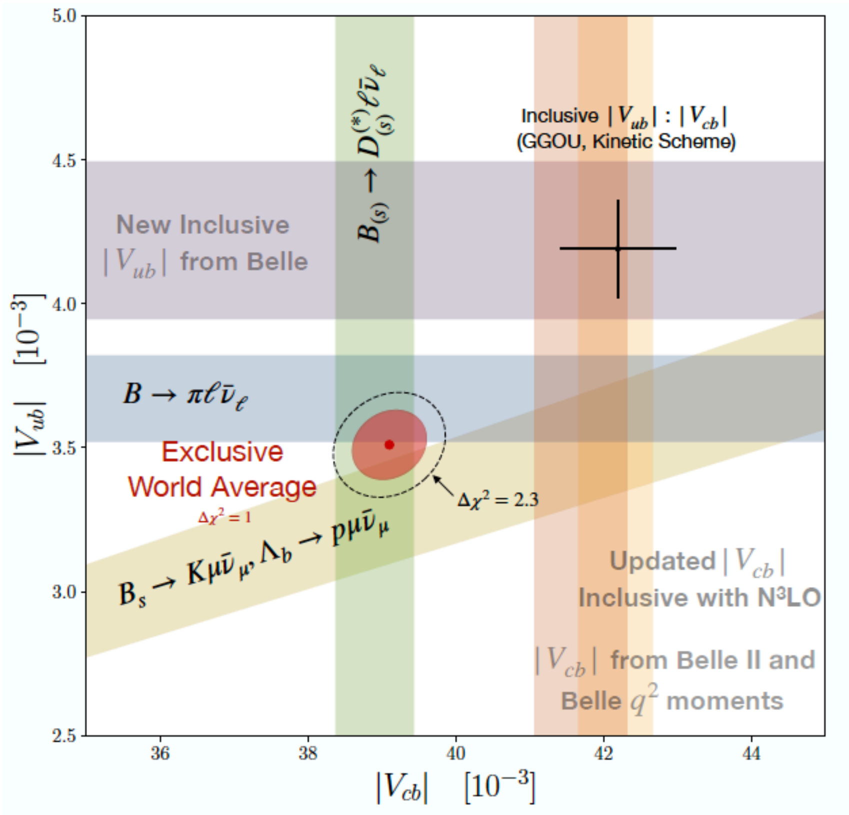
Some prospects for future measurements

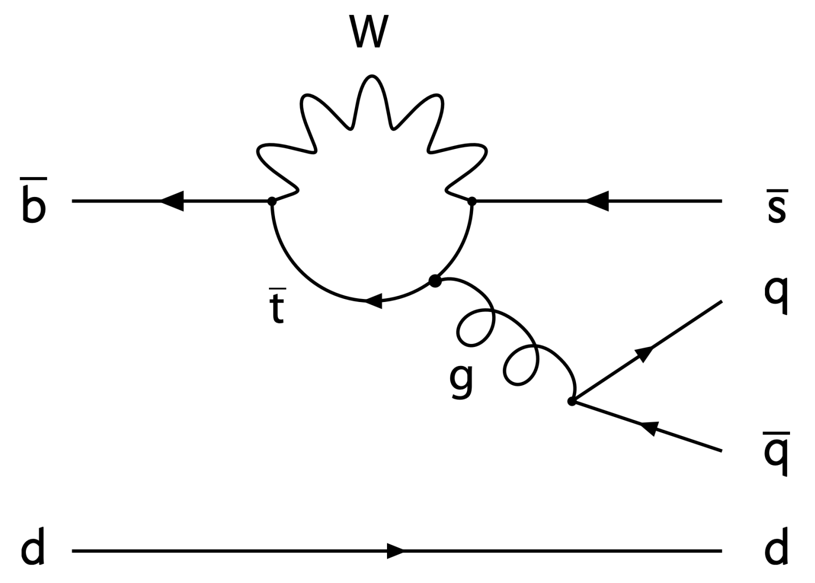
Small part of the broad Belle II physics program



- Testing LFV/LFU and understanding their origins
  - Belle II will measure $R(D^{(*)})$ about 3x more precisely than current world averages, probe NP in angular distributions
  - Belle II expects to discover $B^+ \to K^+ \nu\bar{\nu}$ (BF with 10% uncertainty) and study angular distributions in $B \to K^* \ell\bar{\ell}$

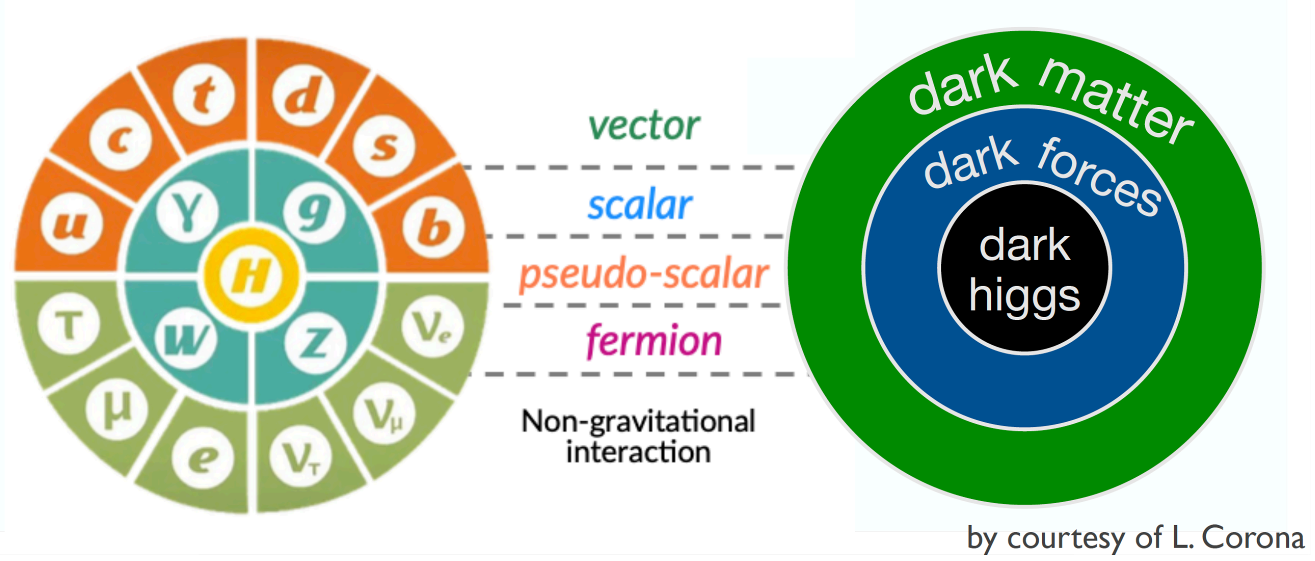
- Checking the unitarity of the CKM matrix to high precision
  - Belle II uniquely positioned to understand/resolve long-standing discrepancy between inclusive/exclusive $|V_{cb}|, |V_{ub}|$ in experimentally clean e^+e^- environment
  - Belle II can measure all CKM angles with high precision





- Identifying new weak (CP-violating) phases in the quark sector
  - Belle II will measure CP asymmetries for decays proceeding via penguin loop transitions $b \to s$ and $b \to d$
  - e.g. unique precision in time-dependent CP asymmetries in $B^0 \to \eta' K^0_S,\ \phi K^0_S$

- Probing the existence of dark-sector particles
  - Unique opportunities at Belle II to uncover dark sector particles
- Reducing the uncertainty in the theory prediction for muon g-2 (see backup)



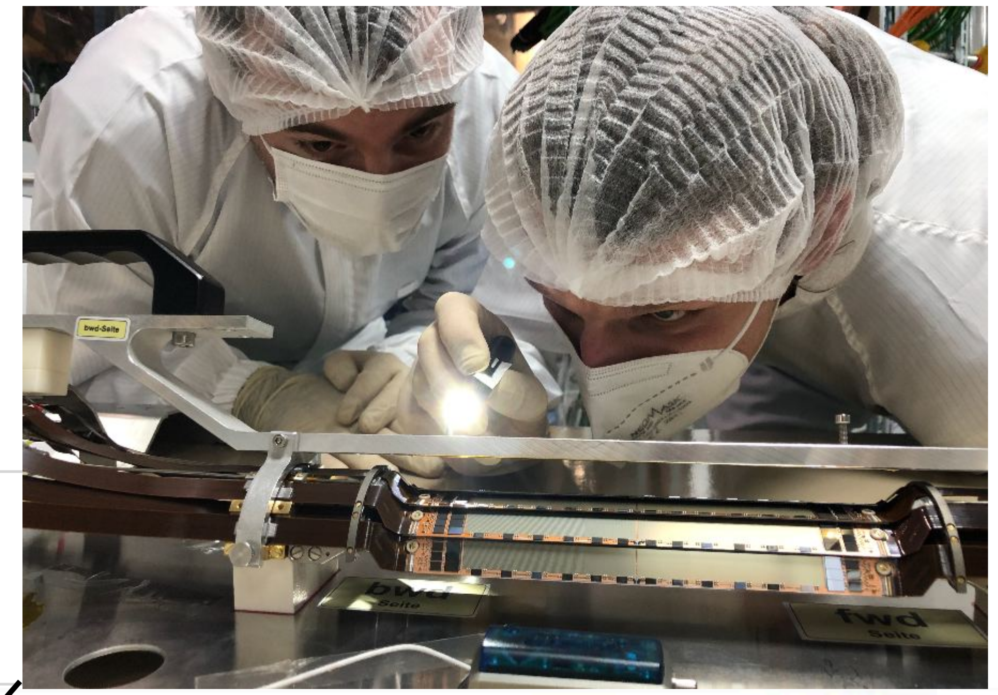
by courtesy of L. Corona

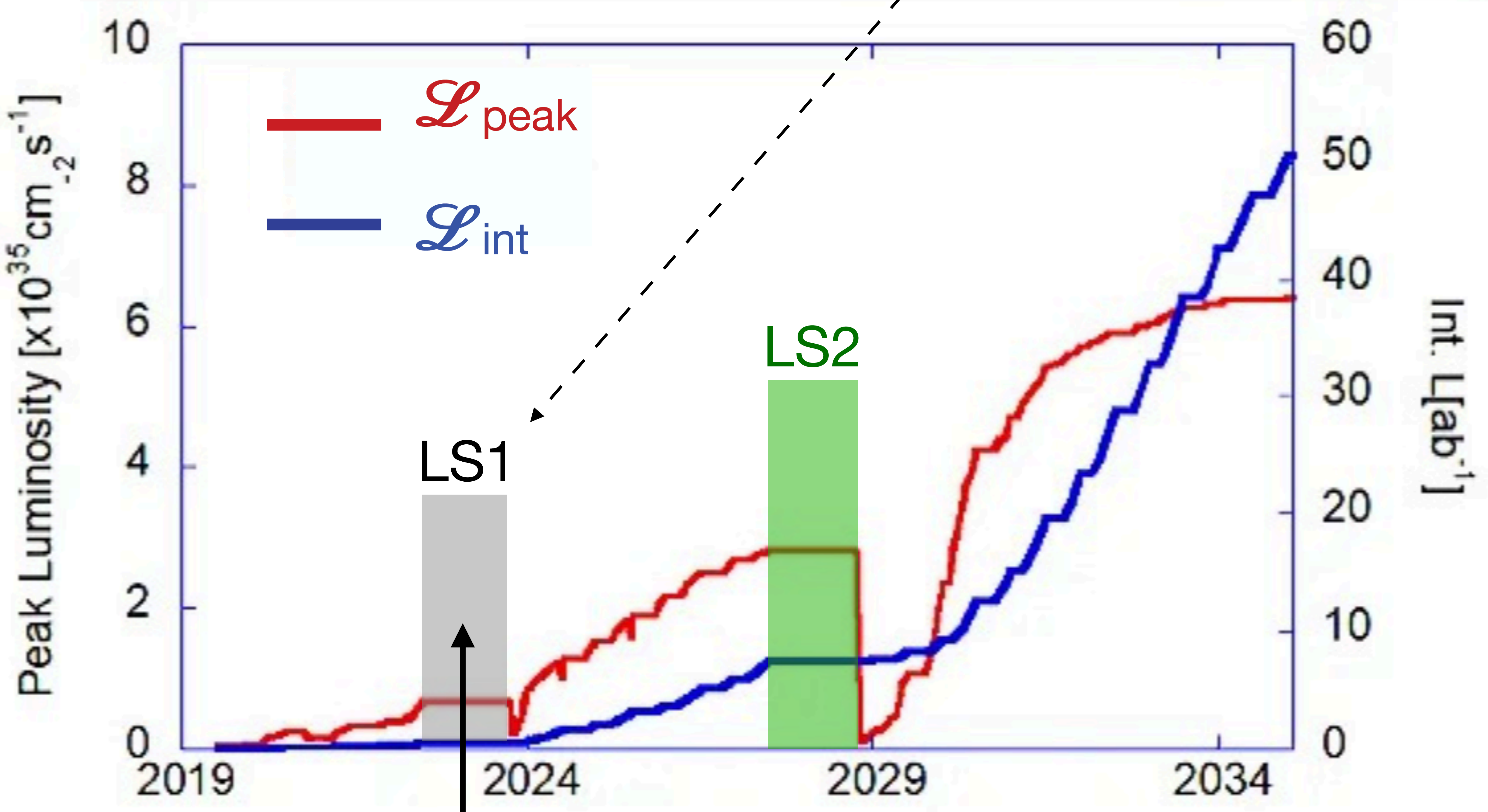
Captions

The road to 50 ab^{-1}

Until 2035

PXD arrives at KEK for testing





You are here:

$\mathscr{L}_{\mathrm{int}} = 424\ \mathrm{fb}^{-1}$ (~half the Belle dataset)

$\mathscr{L}_{\mathrm{peak}} = 4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (world record!) ~5x $\mathscr{L}$(PEP-II)

Belle II

- Long Shutdown 1 (LS1)
  - Ongoing since summer 2022
  - Maintenance and upgrade of machine and detector
  - Data taking will resume in early 2024
- Long Shutdown 2 (LS2)
  - To be confirmed
  - Upgrade of the SuperKEKB interaction region to enable $\mathscr{L}_{\mathrm{peak}} = 6 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Key challenge to increasing beam currents and squeezing beam-size at interaction point: beam-beam blowup

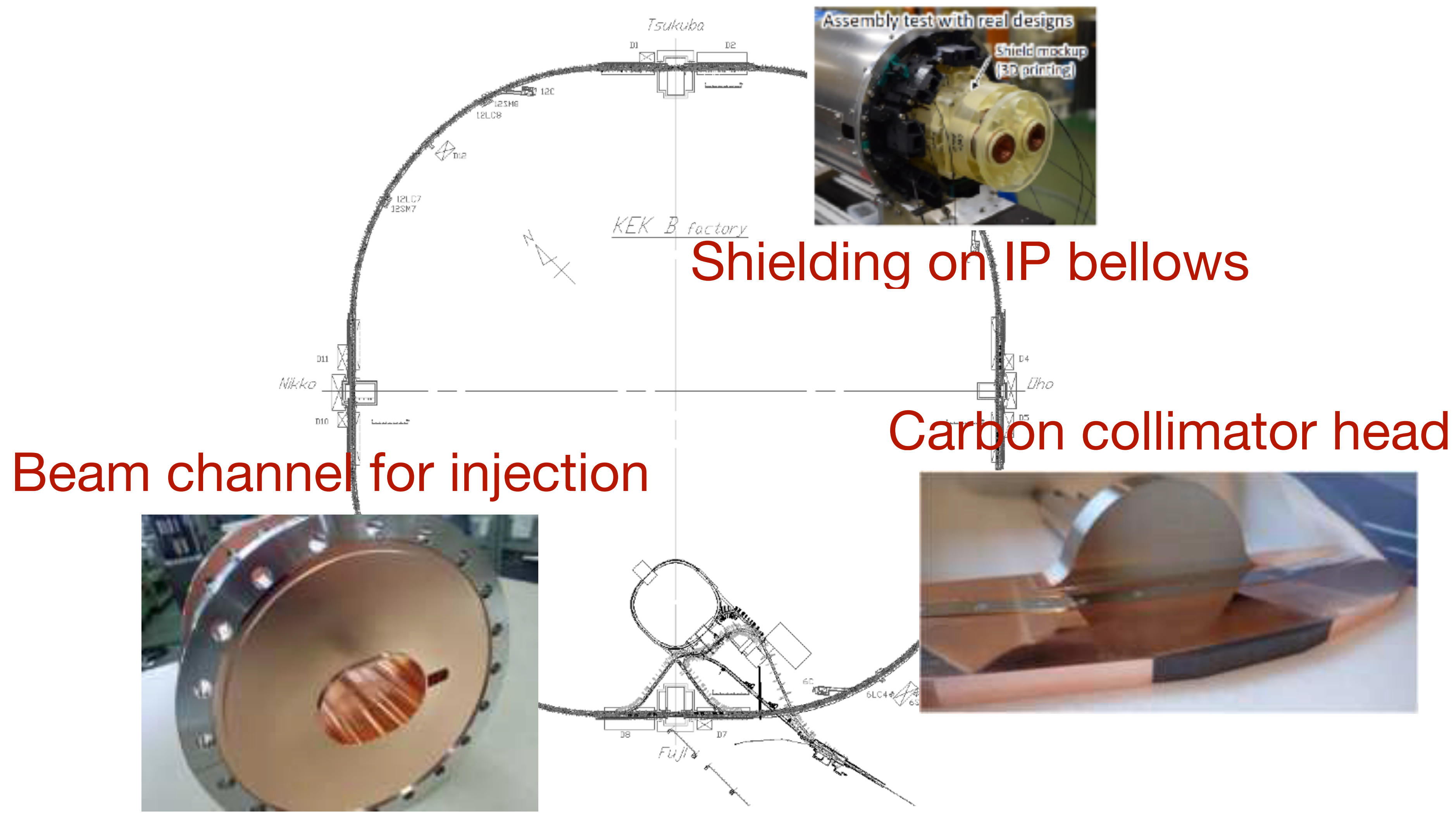
Captions

Improving SuperKEKB luminosity and operational stability

to overcome the challenges of the nano-beam accelerator

- Near-term SuperKEKB modifications to allow for
  - Higher and more stable beam injection
  - Longer beam lifetime
  - Improved beam stability
  - More stable and robust operation

- Accelerator modifications for LS1 (ongoing)
  - Beam background reduction with IR radiation shield modifications and non-linear collimator (also helps with impedance issues)
  - Robust collimator heads as countermeasure against kicker-pulser misfiring
  - New beam pipes, wider aperture at positron injection point for improved injection efficiency
  - Fast kicker magnets to control orbit for two-bunch injection
  - Quadrupole pulse magnet to improve matching of beam optical parameters



- Machine Detector Interface is crucial to cope with the increased beam backgrounds and protect the Belle II detector
  - Improved injection efficiency, reduced dead time
  - Understanding cause of sudden beam loss, add monitors, improved abort system
  - Improved real-time monitoring and mitigation of beam backgrounds via collimation and injection tuning

Captions

US Belle II/SuperKEKB plans and proposal

Optimizing the impact of existing datasets and preparing for upgrades

Belle II

- Current US Belle II funding level: $7.5M/year (BNL, universities)
  - BNL supports GRID computing operations, Universities carry out detector ops and programmatic research
- US Belle II/SuperKEKB “ask” from P5
  - Endorsement/support of three thrusts: SuperKEKB, work force development, and MIE for post-LS2 upgrade
  - Please note that the budget estimates below are approximate

Leverage US national lab accelerator expertise

Task	Estimate (million usd)
SuperKEKB beam-beam R&D, simulation, experiments	1.4/year (minimum 3 years)
University-based work force development	1.8/year
MIE for LS2 detector upgrade	10-15 total

Fully exploit the pre-LS2 data and prepare for the LS2 upgrade

MIE = Major Item of Equipment

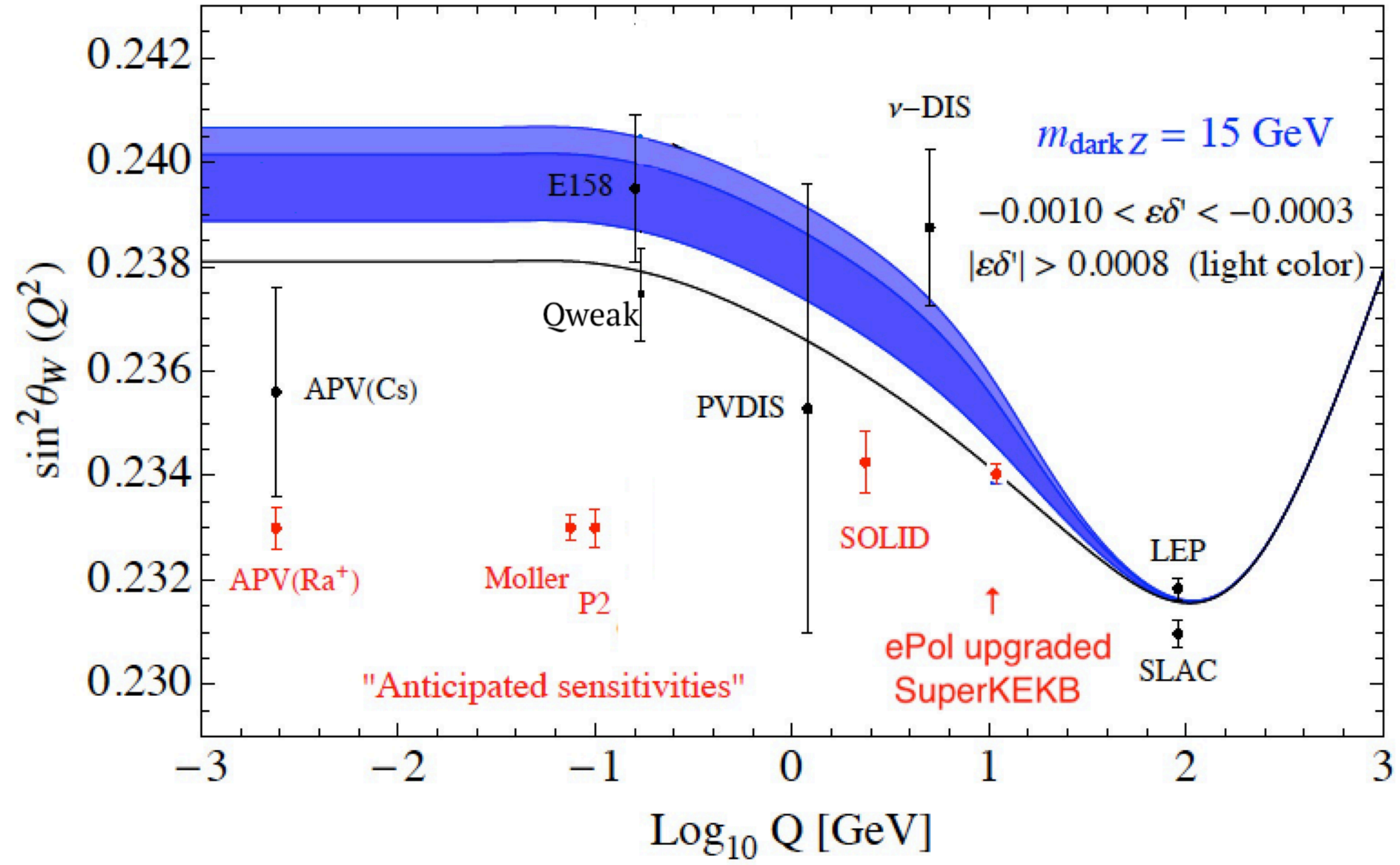
Will include Time Of Propagation and K_L and Muon detectors, background & beam monitoring

Captions

Chiral Belle

SuperKEKB upgrade to polarized beams

Snowmass white paper - arxiv:2205.12847



- Unique sensitivity to dark sector parity violating bosons with masses below the Z^0
- Only facility able to probe neutral current vector coupling universality relations between all fermions at energies below the Z^0 pole
- τ-pairs produced with polarized beams will also provide the only means to measure the third-generation g–2 at a precision comparable to the muon g-2 anomaly, scaled by $(m_\tau/m_\mu)^2$
- Unique and powerful sensitivities to new physics via precision neutral current measurements with polarized beams
- Determine the helicity structure of τ LFV coupling from the final state momenta distributions, e.g. in $\tau \to \mu\mu\mu$
- τ EDM measurements and non-perturbative QCD dynamics at play in hadronization mechanism
- Challenging problem, spin rotator that is transparent to the rest of the SuperKEKB lattice, can be solved!
- Full Conceptual Design in development, to be followed by a technical design and cost estimates
  - Capital costs expected to be substantially less than half the annual power costs of SuperKEKB operation
  - Polarization program could commence while SuperKEKB completes delivery of 50 ab^{-1} to Belle II

Captions

Belle II featured in Snowmass 2021 Report and ESG

Key part of Rare Processes and Precision Measurements Frontier

Belle II

“the Rare Processes and Precision Measurement Frontier proposes that the upcoming P5 adds a new science Driver: flavor physics as a tool for discovery”

“Priorities for the next few years are to complete the analysis of the Muon g – 2 experiment, begin taking data with Mu2e, and continue taking and analyzing data at Belle II and LHCb"

"Belle II and LHCb have the unique potential to unveil new physics by confirming intriguing hints of deviations from the SM that have been recently observed… or finding new unexpected outcomes in the study of rare and forbidden decays…”

“The U.S. flavor community is well-positioned to lead key aspects of the physics, computing, and detector construction in all of these experimental programs”

European Strategy Group: ”The quest for dark matter and the exploration of flavor and fundamental symmetries are crucial components in the search for new physics.”

Captions

Summary and conclusions

- The physics program of Belle II has outstanding potential for discovering non-SM physics over the next decade
  - Also, if unambiguous non-SM physics signals are observed in flavor-physics measurements made at other experiments, independent measurements at Belle II will be important
- The broad program of fundamental weak interaction measurements, the current hints of non-SM flavor signals, as well as the exciting possibility of New Physics discoveries in searches unique to Belle II warrant enhanced U.S. investment in the Belle II and SuperKEKB and their upgrades
- Given the NP discovery potential of Belle II, the track record of the preceding Belle experiment, and the modest financial commitment to the US HEP budget, the US investment in Belle II will produce high impact physics at a world-class e^+e^- facility for modest cost
  - Note that Belle II @ SuperKEKB represents a significant Japanese investment, 310 oku-yen ($300 M*) for construction and 90 oku-yen/year ($90 M/year*) for operations. These values are calculated in Japanese accounting and do not include personnel, administration, and contingency as in US project accounting
- With half the dataset of previous B-factories, Belle II is already producing world-leading results
- Many opportunities for initiatives by early career researchers

* The dollar-yen exchange rate has fluctuated recently.
These estimates assume 100 yen/dollar as in 2012.

Captions

Extra slides

Details related to “ask”

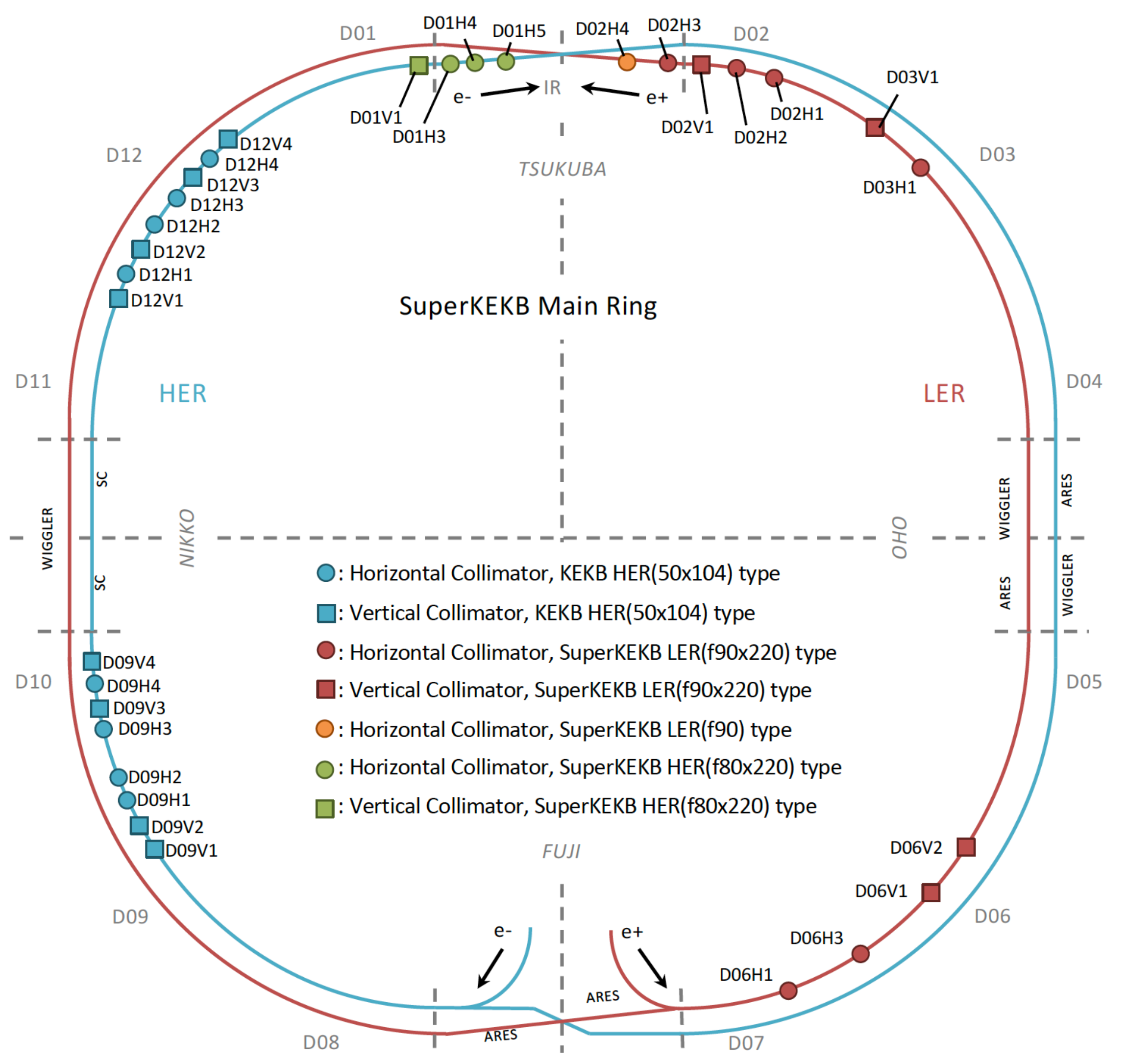
- Leverage US national lab accelerator expertise for SuperKEKB beam-beam R&D, simulation and experiments
  - 3 x $250k (accelerator PD at SLAC, Cornell, BNL), 3 x 0.2 FTE = $475k senior sci. to engage PD + $60k/lab travel/materials
  - Need significant machine and MDI improvements to realize $2.5 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$ before LS2
  - Synergy with FCCee R&D and allows for training accelerator physicists on an actual frontier e^+e^- facility
- University-based Work Force Development to fully exploit the pre-LS2 data and prepare the LS2 upgrade
  - Total cost is 6 x 300 K/year (includes postdocs, grad students) = 1.8 M/year
  - We plan to add 6 junior faculty at existing or new Belle II institutes and will request programmatic funding to support these faculty
  - Target faculty hires capable of contributing to one of the following pressing US HEP needs called out at Snowmass
    - Training and development on the instrumentation frontier https://arxiv.org/abs/2209.14111
    - Development of AI/ML techniques on the front-end, trigger and/or offline software https://arxiv.org/abs/2209.07559
    - Coordination with worldwide partners on training and development for software and computing infrastructure to enable use of heterogeneous resources such as HPCs (including GPU farms), cloud computing etc https://arxiv.org/abs/2209.08868
  - This work-force development plan will address the diversity and age profile issue of Belle II faculty
- MIE for the LS2 detector upgrade ~2027-2029: $10-15M total
  - This will include TOP (Time Of Propagation), KLM and background and beam monitoring
  - Total scaled from 2012-2016 US Belle II construction MIE, removing quartz acquisition, plus inflation 3%/year for 15 years

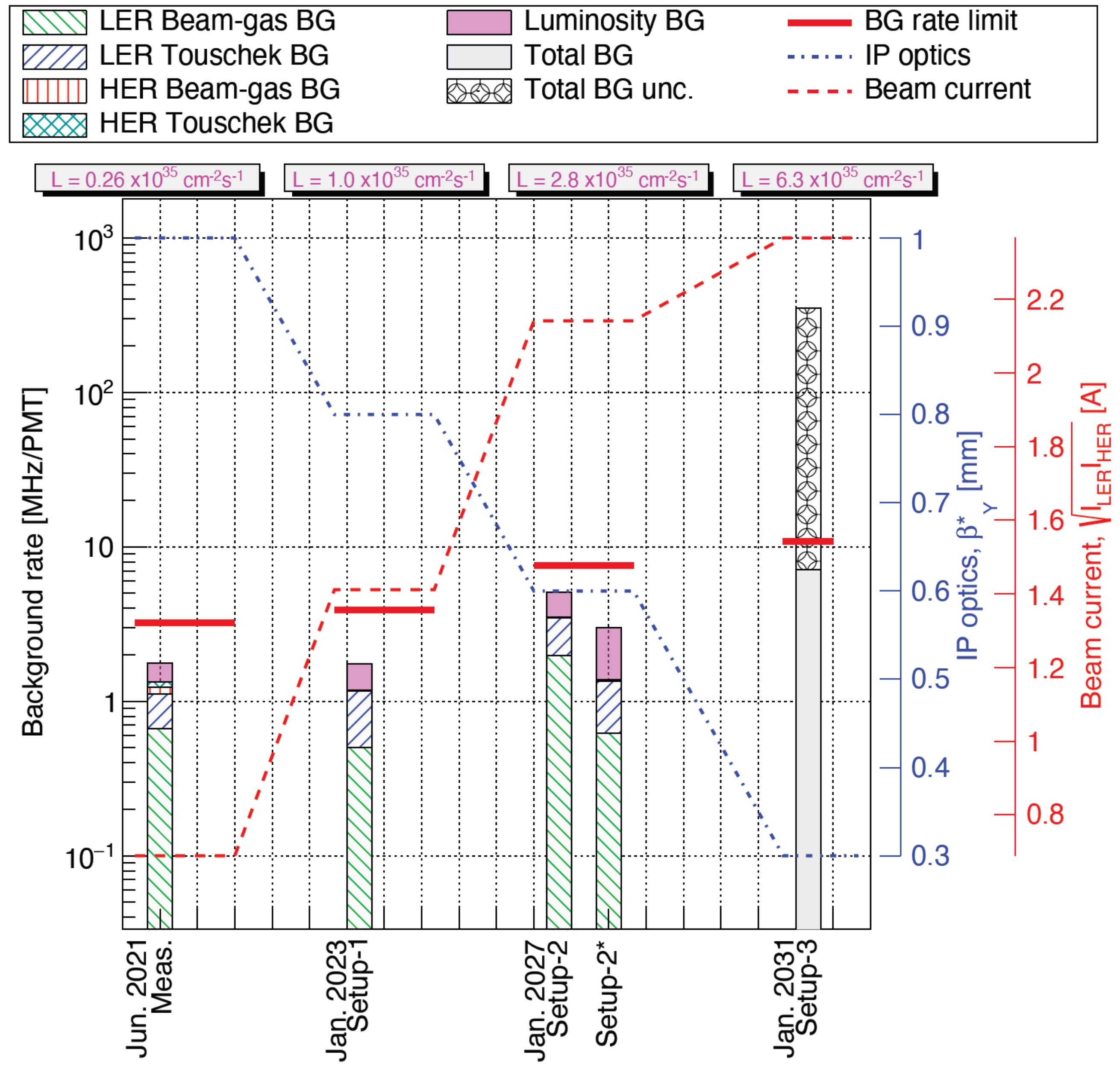
https://arxiv.org/abs/2203.05731

Beam background expectations for Belle II at SuperKEKB

In close collaboration with US, EU, and Asian accelerator labs

- SuperKEKB accelerator has already reached $\mathscr{L} = 4.7 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, a world record, with a betatron function of $\beta_y^* = 1.0\ \mathrm{mm}$
  - Target $\mathscr{L} = 6 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ for $\beta_y^* = 0.3\ \mathrm{mm}$
- Several sub detectors at close-to-tolerable backgrounds at peak $\mathscr{L}$
  - Most vulnerable, Time Of Propagation (TOP) and Central Drift Chamber (CDC)
  - Beam backgrounds studied extensively in early phases of SuperKEKB running





- Beam background mitigation (beam collimation, specialized shielding) to prevent accidental damage, deterioration, reduced performance
- Extensive simulations, corrections, projections for future running
  - Backgrounds should remain high, but acceptable up to $\mathscr{L} = 2.8 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ for $\beta_y^* = 0.6\ \mathrm{mm}$
  - Further predictions highly uncertain due to IR redesign in LS2
- Machine Detector Interface (MDI) is crucial to cope with the increased background and protect the Belle II detector

What happens beyond 50 ab^{-1}?

- Belle II
  - Higher sensitivity to decays with photons and neutrinos (e.g. $B \to K\nu\bar{\nu},\ \mu\bar{\nu}$), inclusive decays, time dependent CPV in B_d, τ physics
- LHCb
  - Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavors (e.g. Λ_b), high boost for fast B_s oscillations
- Overlap in key areas to verify discoveries
- **Upgrades**
  - Most key channels will be statistically limited (not theory or systematics)

Observable	2022 Belle(II), BaBar	2022 LHCb	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	LHCb 50 fb^{-1}	Belle-II 250 ab^{-1}	LHCb 300 fb^{-1}
$\sin 2\beta/\phi_1$	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/ϕ_3	11°	4°	4.7°	1.5°	1°	0.8°	0.35°
α/ϕ_2	4°	–	2°	0.6°	–	0.3°	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	4.5%	6%	2%	1%	2%	< 1%	1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	–	0.03	0.015	–	0.007	–
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	–	0.07	0.04	–	0.018	–
$S_{CP}(B \to K^{*0}\gamma)$	0.32	–	0.11	0.035	–	0.015	–
$R(B \to K^*\ell^+\ell^-)^\dagger$	0.26	0.12	0.09	0.03	0.022	0.01	0.009
$R(B \to D^*\tau\nu)$	0.018	0.026	0.009	0.0045	0.0072	<0.003	<0.003
$R(B \to D\tau\nu)$	0.034	–	0.016	0.008	–	<0.003	–
$\mathcal{B}(B \to \tau\nu)$	24%	–	9%	4%	–	2%	–
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	–	–	25%	9%	–	4%	–
$\mathcal{B}(\tau \to e\gamma)$ UL	42×10^{-9}	–	22×10^{-9}	6.9×10^{-9}	–	3.1×10^{-9}	–
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	46×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	1.1×10^{-9}	0.07×10^{-9}	5×10^{-9}

Table 1: Projected precision of selected flavour physics measurements at Belle II and LHCb.(The † symbol denotes the measurement in the $1 < q^2 < 6$ GeV/c^2 bin.)

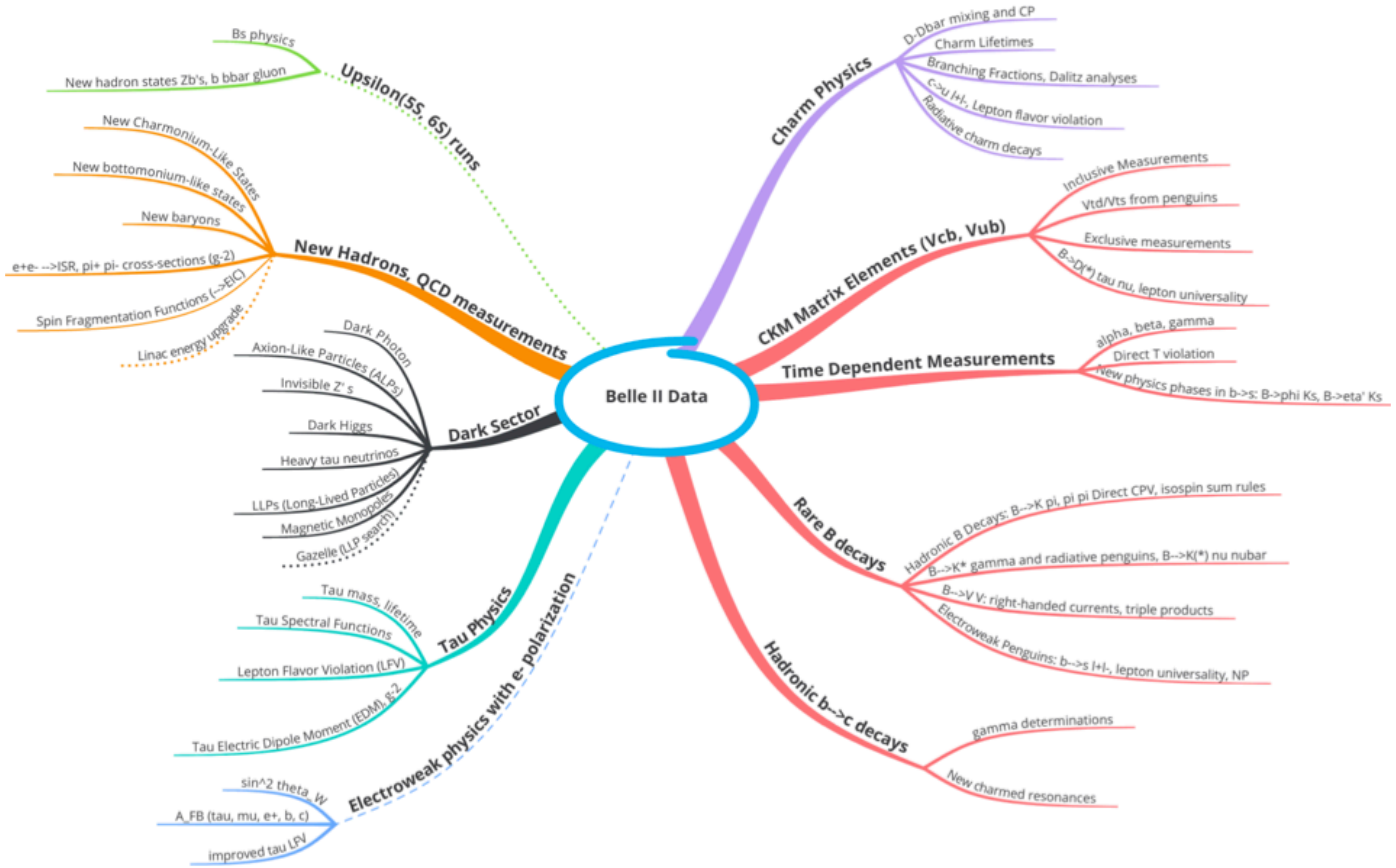
JAHEP report to Snowmass:
https://arxiv.org/abs/2203.13979

Consideration of further luminosity upgrade and electron polarization capability of SuperKEKB are started for ultimate new physics searches with heavy flavor quarks and leptons including τ lepton g-2 in light of the muon g-2 anomaly

The Belle II Physics Program

A snapshot

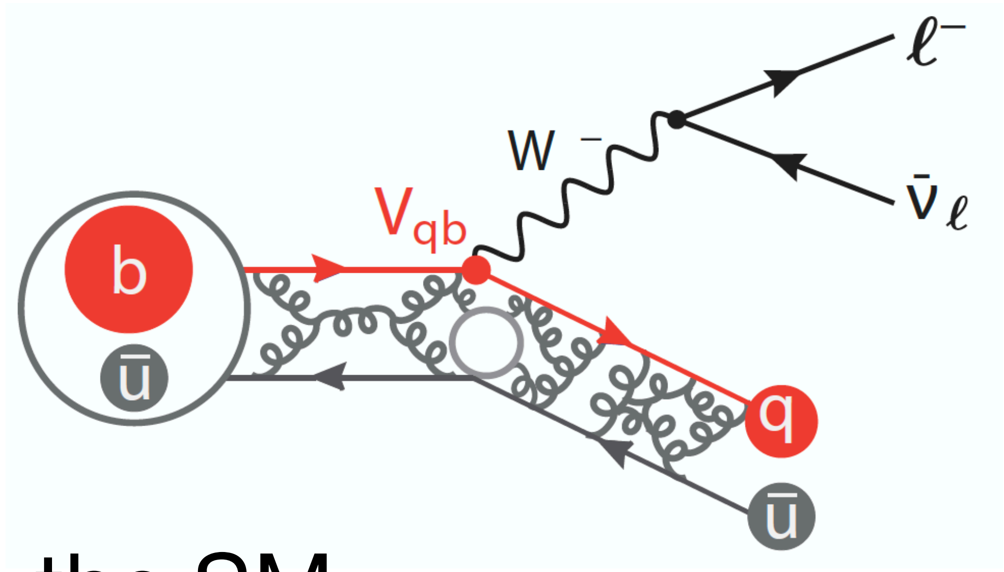
- Goal: uncover new physics beyond the SM
- Will contribute to NP searches in many ways
  - Improved precision on SM physics, CPV
  - LFV, LFU, EDM
  - Unique searches in Dark Sector
- … with many analysis types
  - time-dependent searches
  - missing energy and missing mass
  - Dalitz plot (multi-body) studies
- Some of which are unique to Belle II
  - e.g. inclusive decays and absolute branching fraction measurements that may be impractical at hadron machines



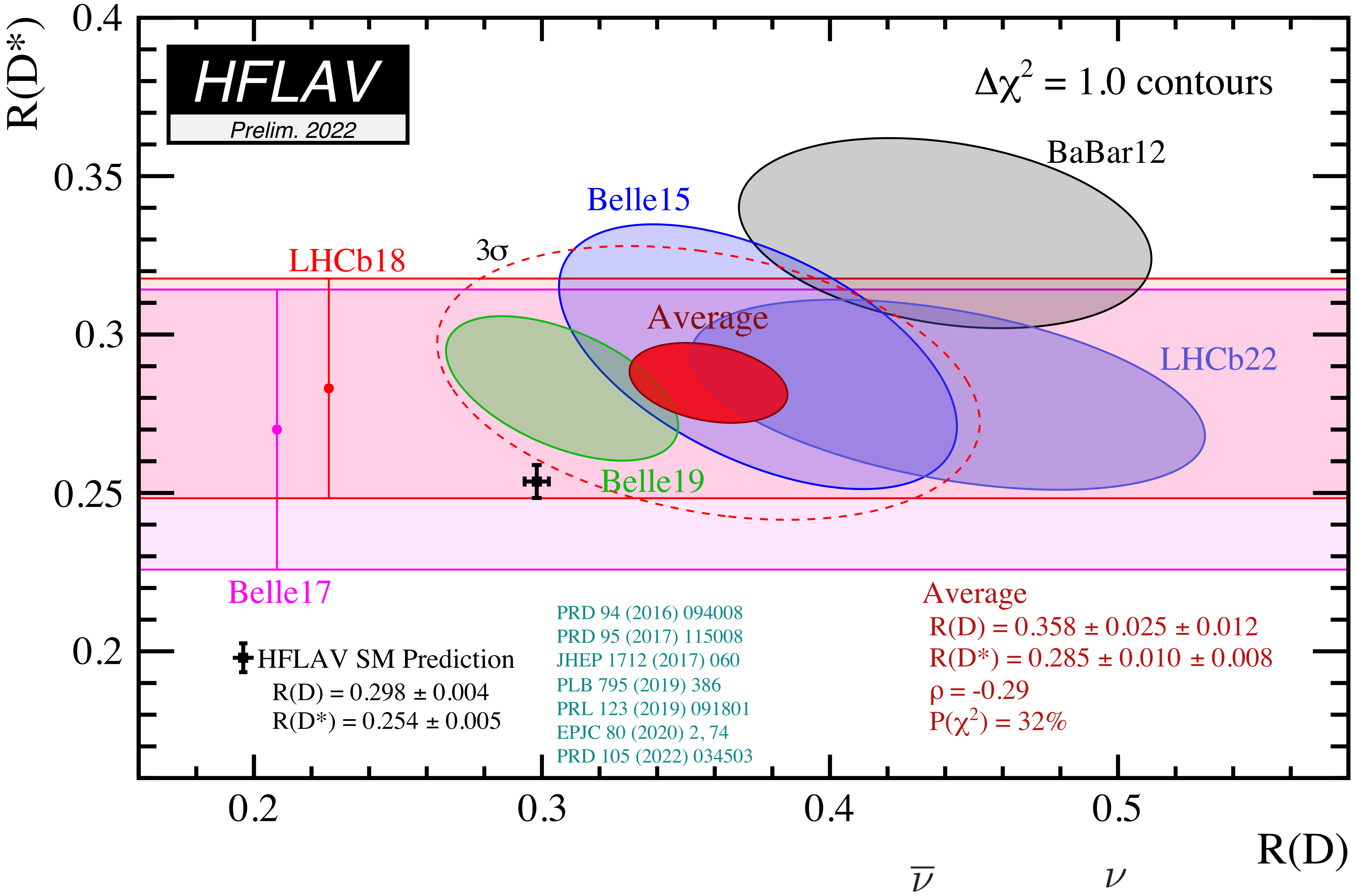
Captions

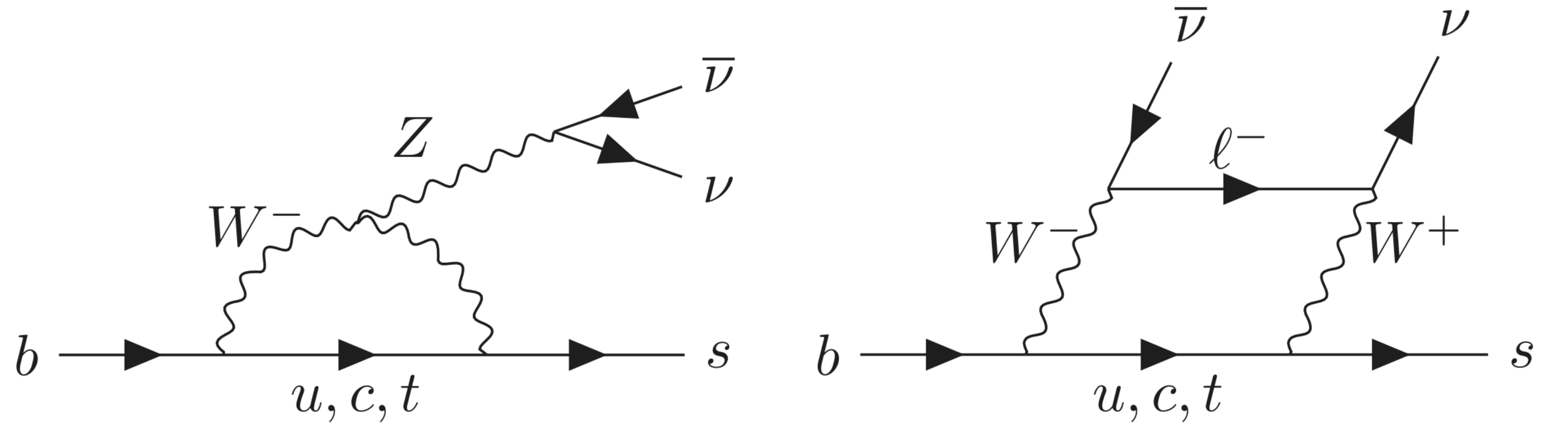
Testing LFV/LFU

and understanding their origins



- Universality of the lepton coupling to the W gauge boson is fundamental in the SM
- Semileptonic B decays sensitive to NP
  - Flavor-dependent fermion couplings could violate LFU
  - Most systematic uncertainties, CKM element, and form factors, cancel in ratios
  - Belle II will measure $R(D^{(*)})$ about 3x more precisely than current world averages
  - Can also probe inclusive semi-tauonic B decays (different theoretical uncertainties), angular distributions sensitive to NP
  - Belle II expects to discover $B^+ \to K^+\nu\bar{\nu}$ (BF measurement with 10% uncertainty) and study angular distributions in $B \to K^*\ell\bar{\ell}$
- Belle II will investigate LFV with τ decays in many modes
  - Sensitivity of dozens of modes will be improved by up to two orders of magnitude

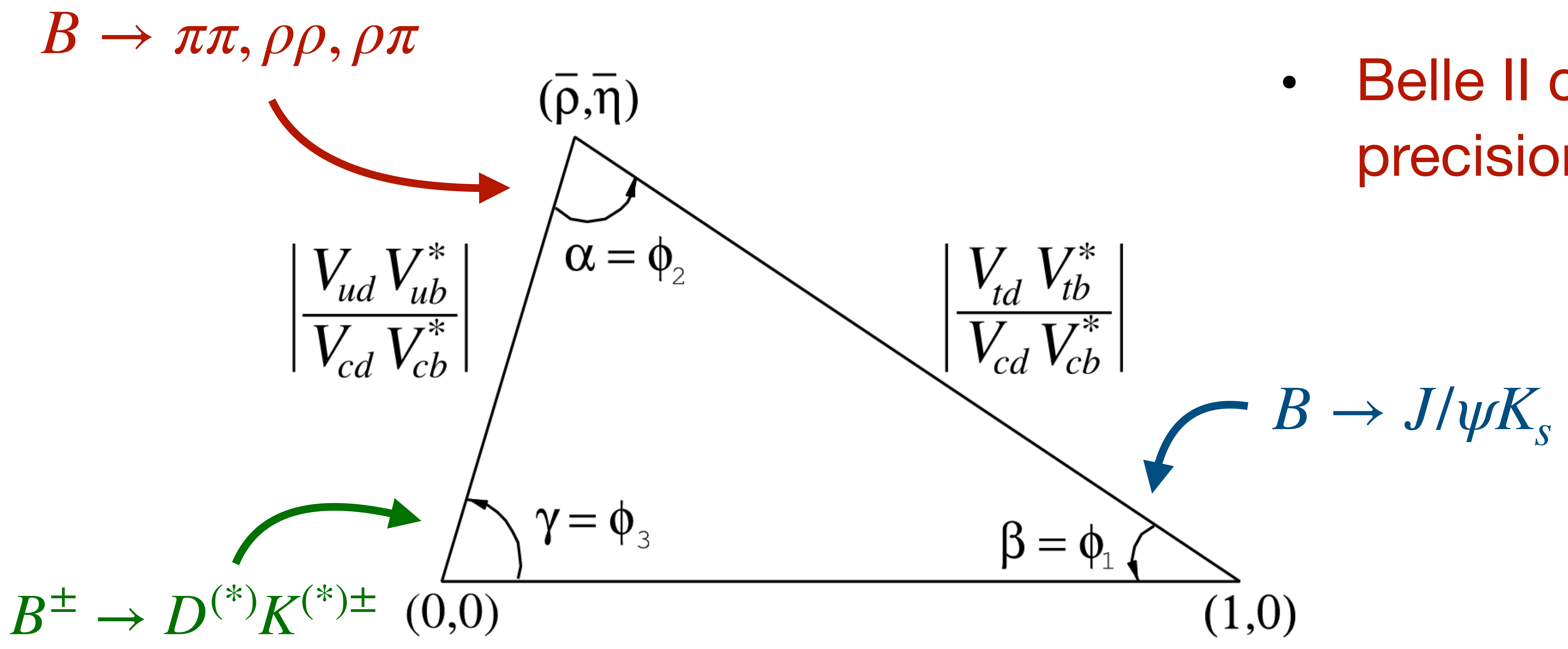




FCNC potentially sensitive to non-SM contributions via new particles contributing both in the box and in the penguin diagrams

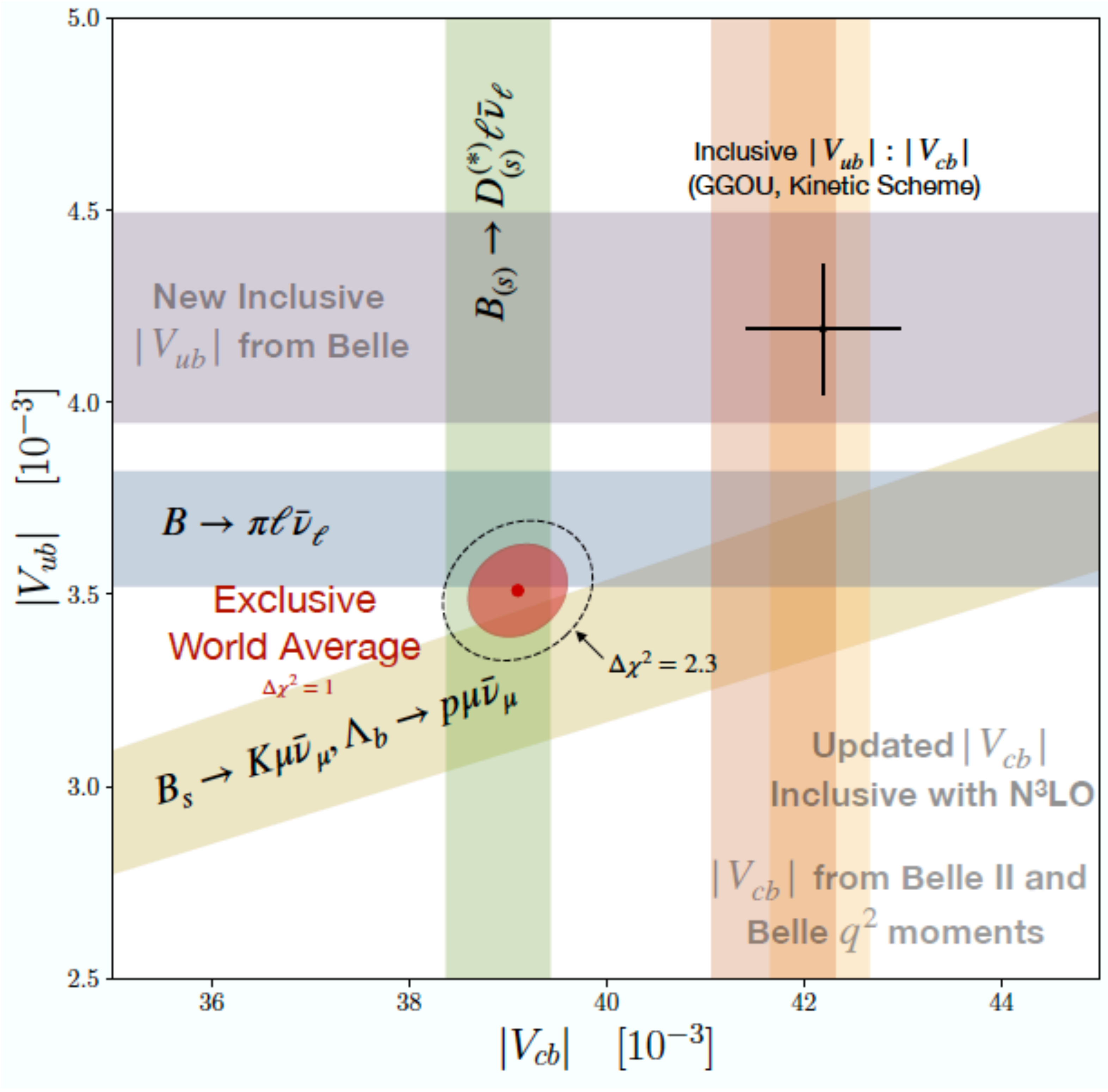
Checking the unitarity of the CMK matrix to high precision

Belle II can measure all CKM angles with high precision



- Belle II can measure α/ϕ_2 with a world-leading precision of less than 1°

- Long-standing discrepancy between inclusive/exclusive $|V_{cb}|, |V_{ub}|$
  - Could indicate presence of non-SM partial widths
  - Belle II uniquely positioned to understand/resolve discrepancies in experimentally clean e^+e^- environment
- Measured $|V_{us}|$ systematically smaller than CKM unitarity constraints
  - Inclusive τ decays at Belle II provide alternate approach (different systematics than semileptonic kaon decays)

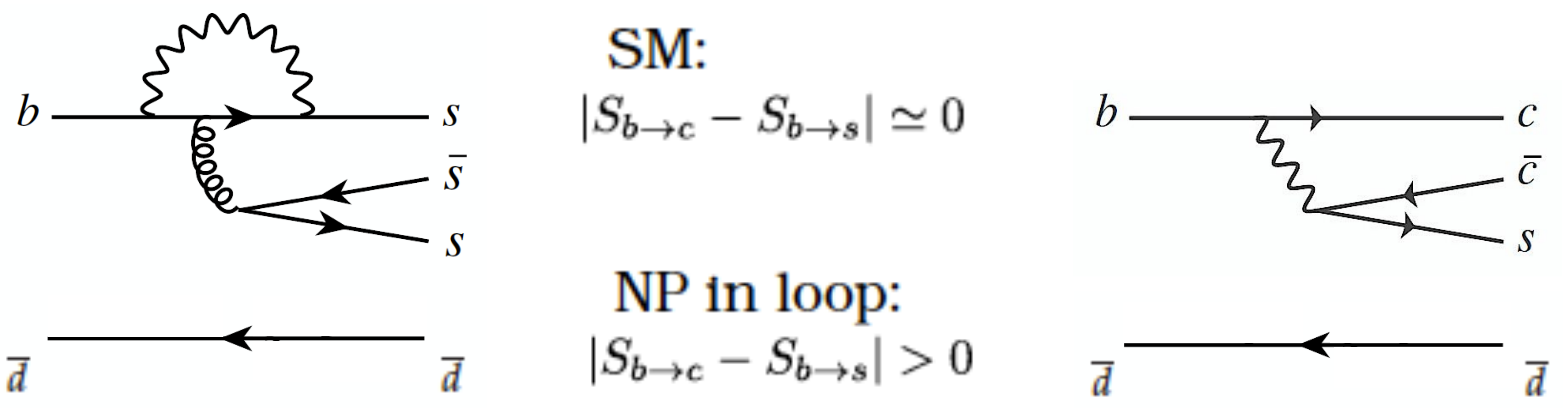


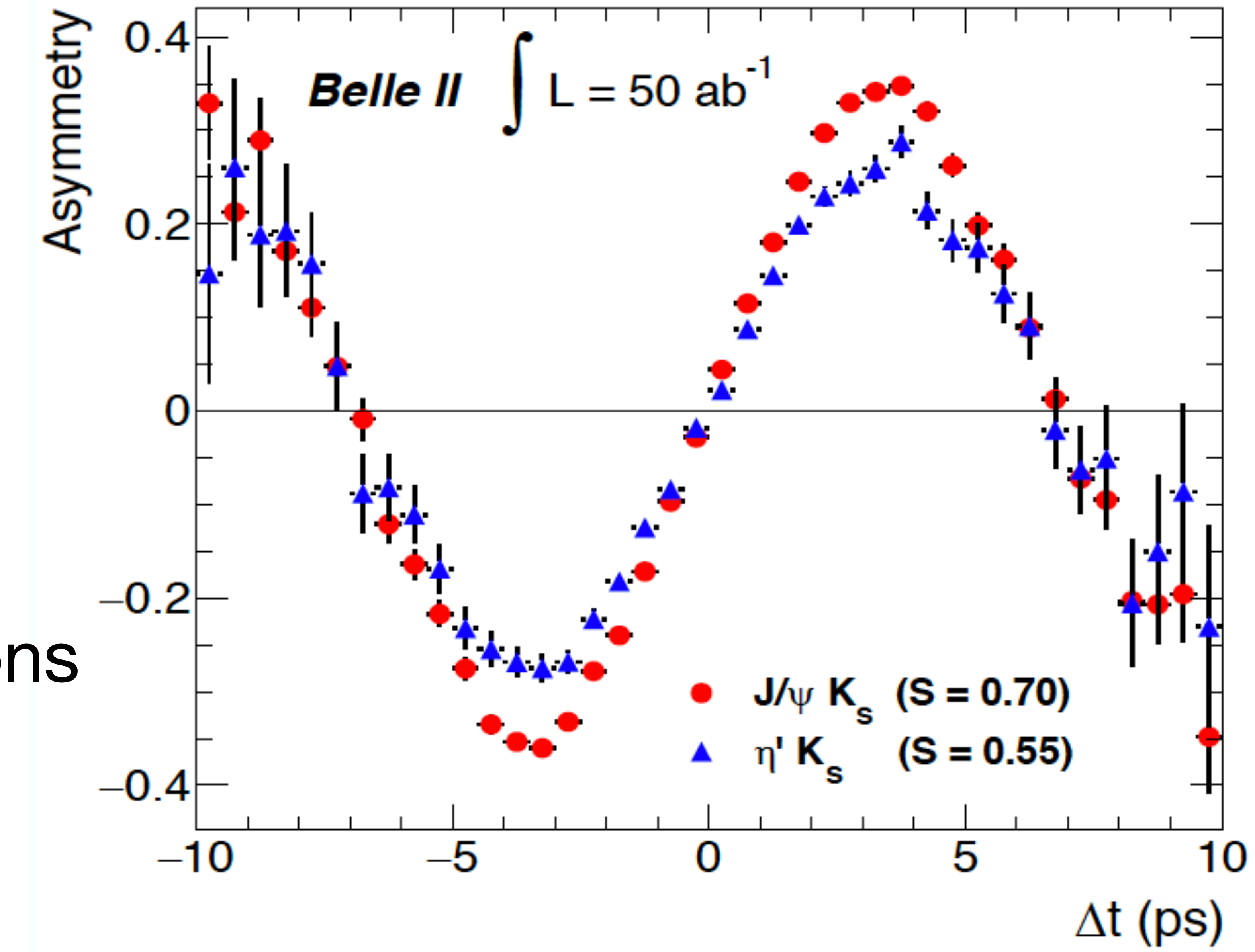
HFLAV 2021, plus recent results (credit F. Bernlochner)

Identifying new weak (CP-violating) phases in the quark sector

High sensitivity to New Physics

- High sensitivities to new weak phases from non-SM processes in CP asymmetries for decays proceeding via penguin loop transitions $b \to s$ and $b \to d$
  - Belle II will measure such asymmetries in variety of charged and neutral final states
  - e.g. unique precision in time-dependent CP asymmetries in $B^0 \to \eta' K_S^0, \phi K_S^0$

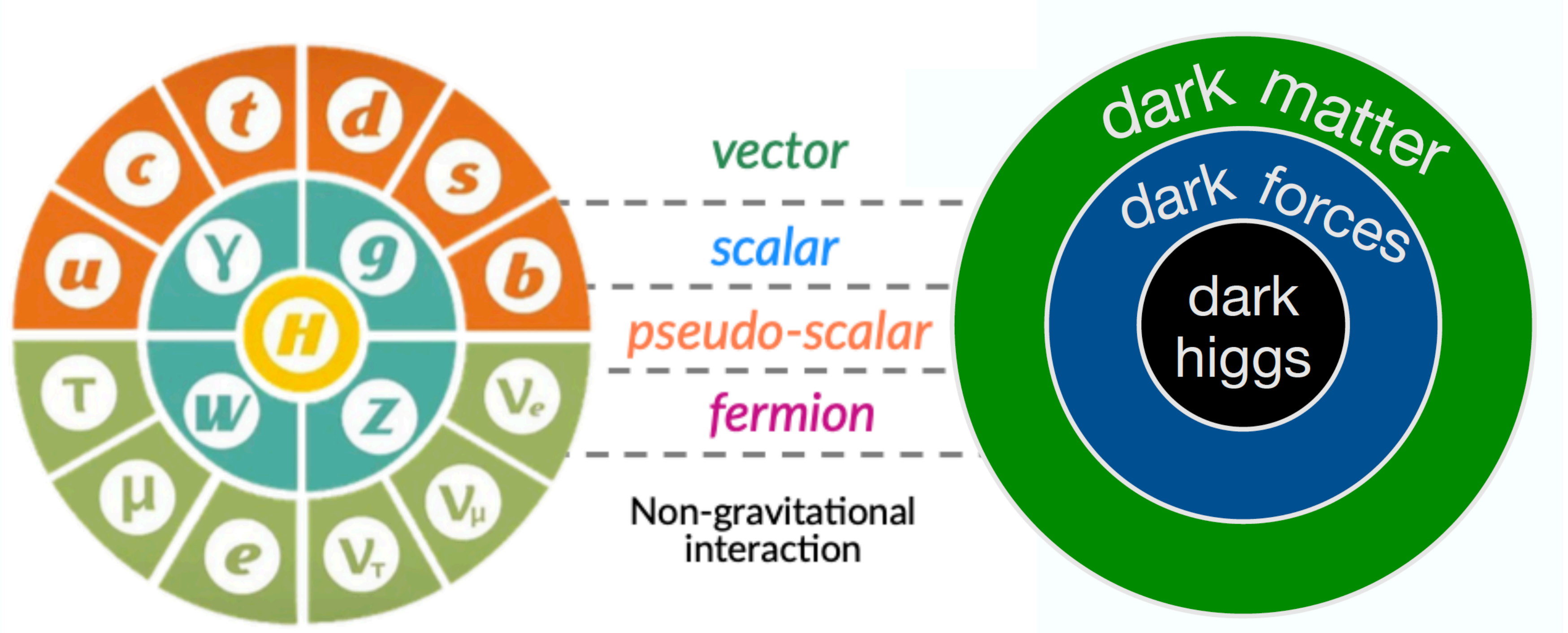




- Charged and neutral $B \to K\pi$ deviate from expectations naive isospin relations
  - Belle II can determine all terms of BFs and CP asymmetries with high precision, including $K_S^0\pi^0$ (dominates sensitivity of sum rule)
- Belle II will measure time-dependent CPV in $b \to s\gamma$ that can arise from right-handed currents
- Will also search for CPV in many charm hadron decays, including $D \to \pi^+\pi^0$ (unambiguous evidence for NP)

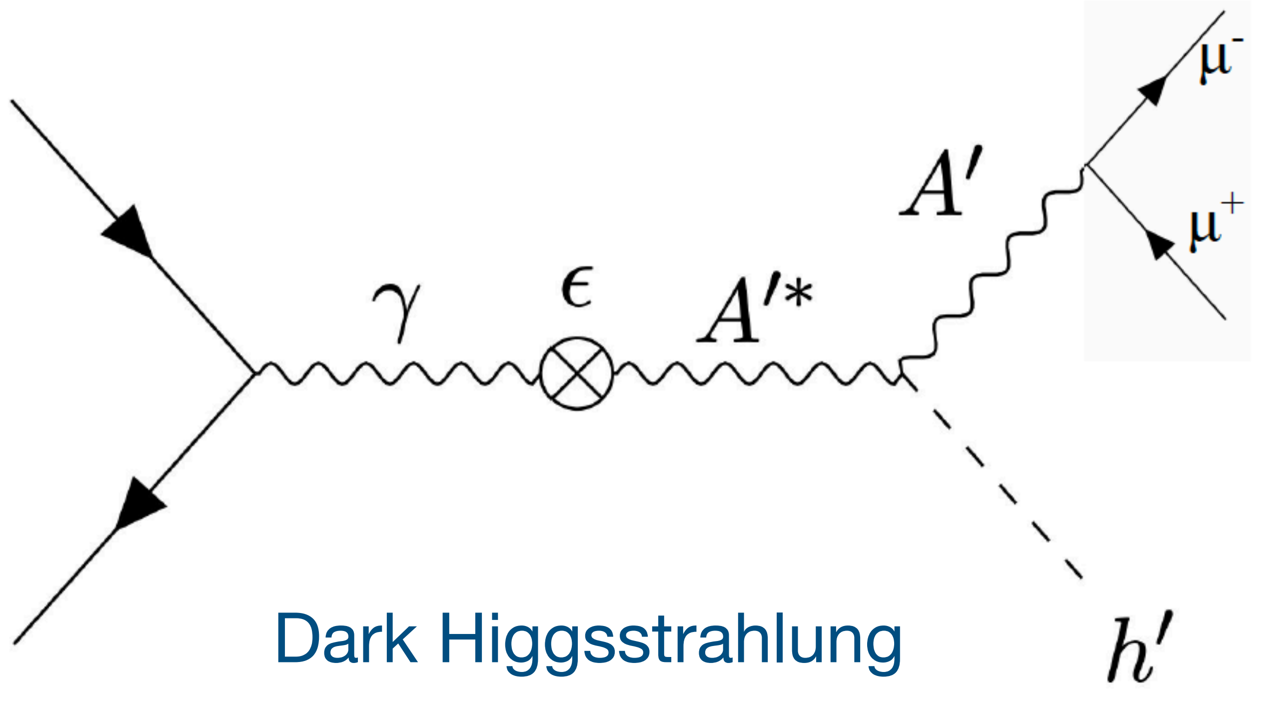
Probing the existence of dark-sector particles

Belle II already has several world leading results

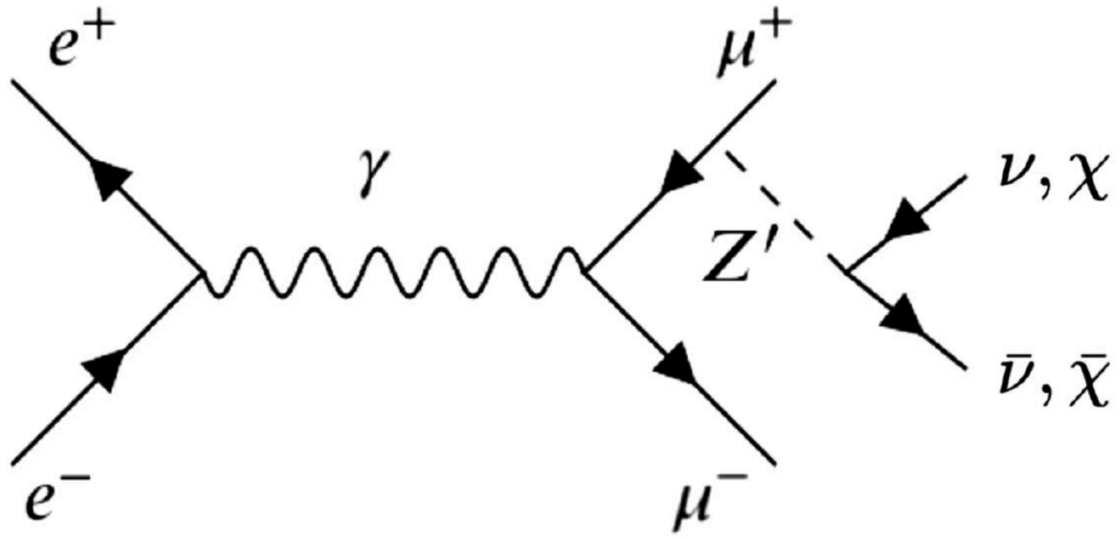


by courtesy of L. Corona

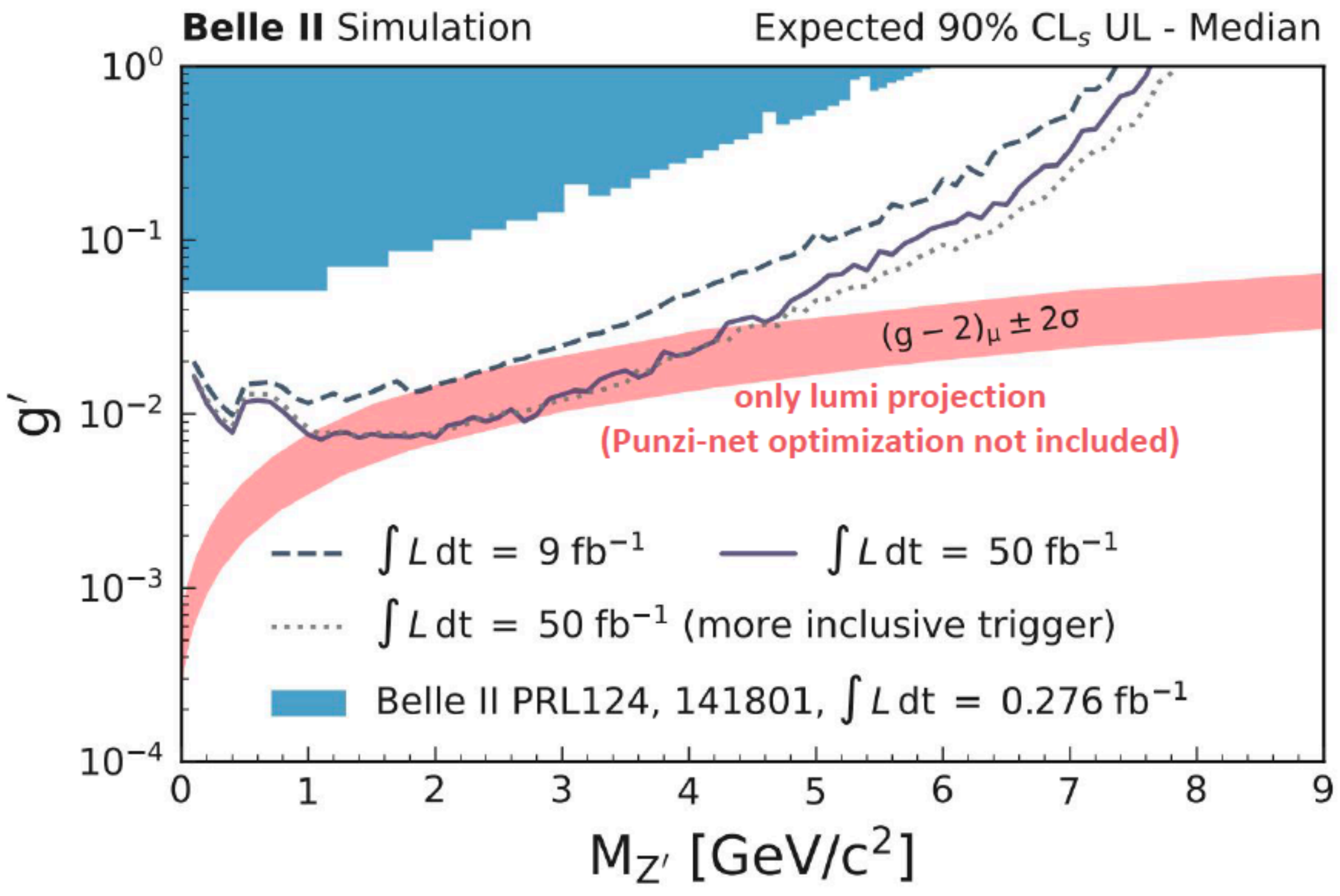
- Belle II can search for light DM with masses $\mathcal{O}$(MeV-GeV)
  - Interest growing after null direct searches at LHC
  - Theoretical models predict light mediators that couple DM to SM particles
  - Unique opportunities at Belle II to uncover dark sector particles



Dark Higgsstrahlung



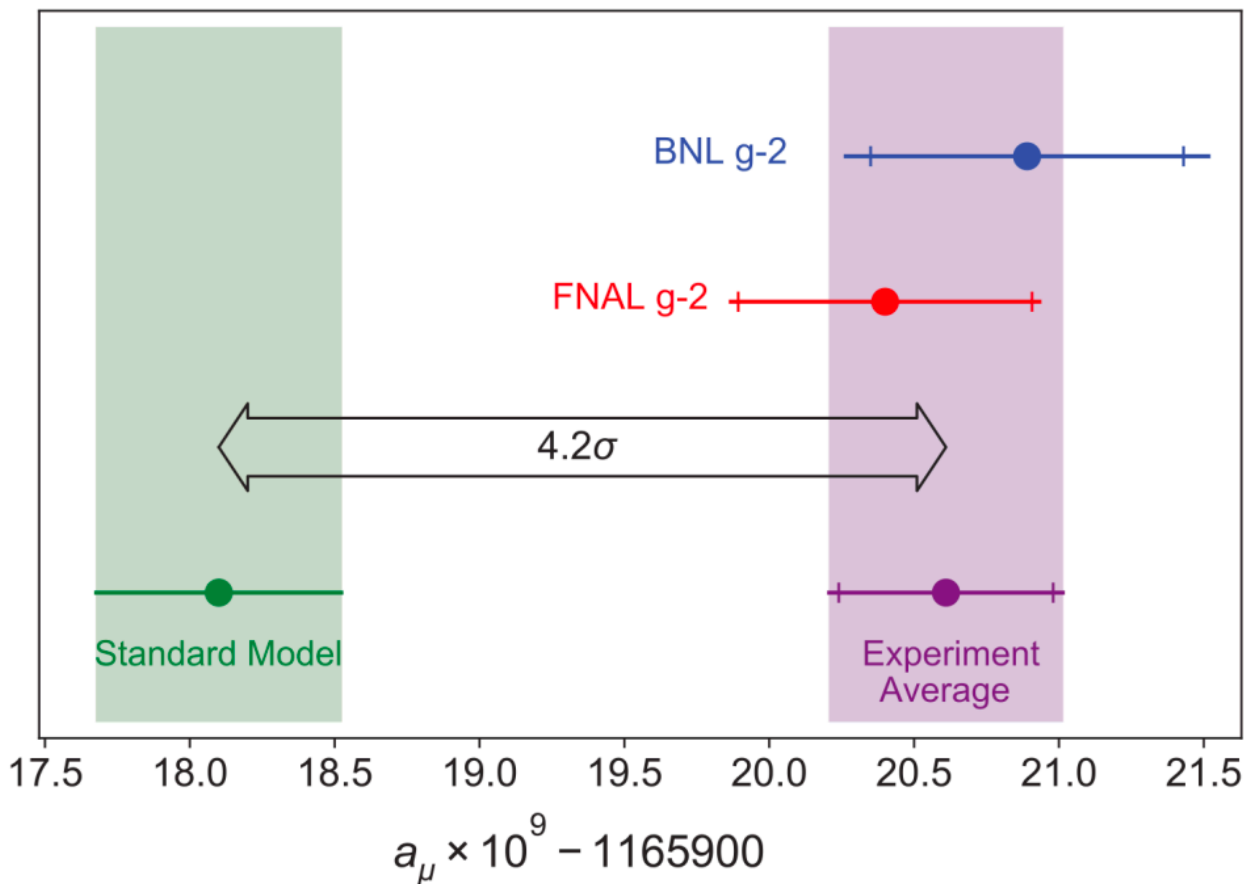
Invisible Z'

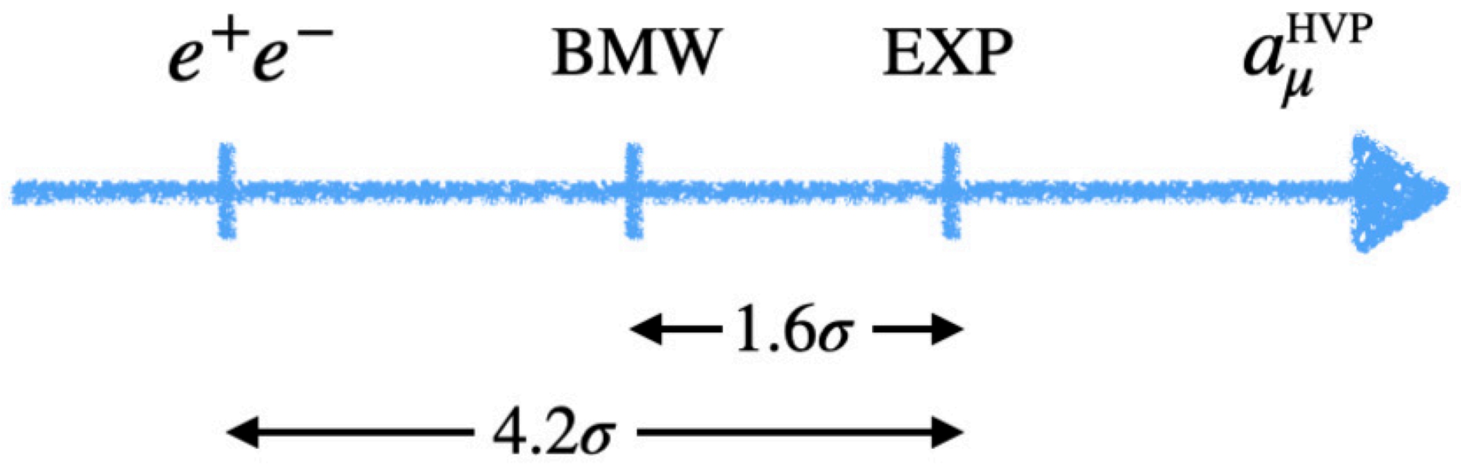


- Primary challenge at Belle II: suppress the large SM background, isolate experimental signature
  - Dedicated low-multiplicity triggers
  - Precise knowledge of acceptance and efficiency

Reducing the uncertainty in the theory prediction for muon g-2

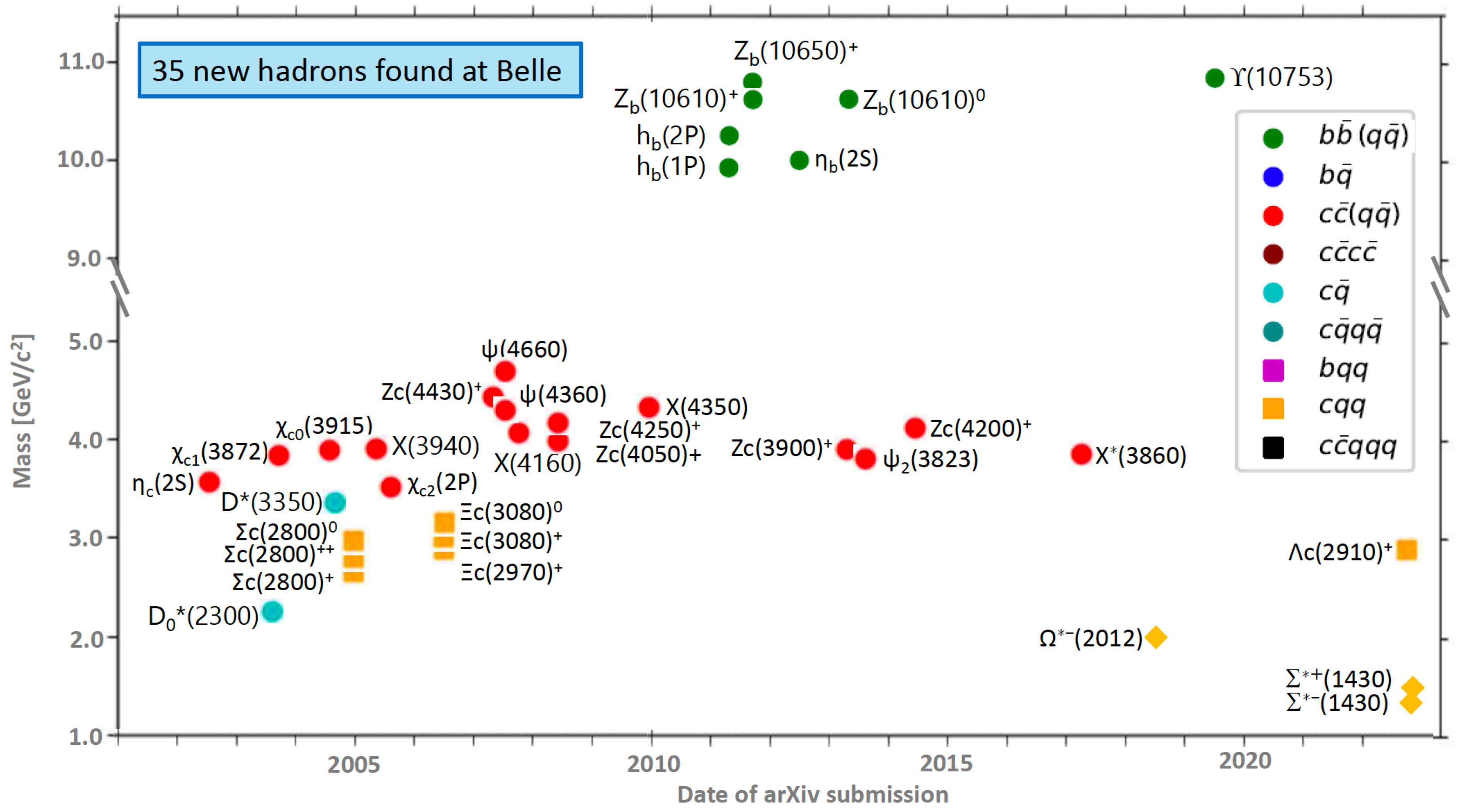
- Important measurement of US HEP program
- Belle II can reduce the dominant theoretical uncertainty with a more precise measurement of the $e^+e^- \to \pi^+\pi^-$ cross section with high statistics data





Understanding the role of QCD in production and binding of hadrons

- Exotic QCD states including tetraquarks and QCD molecules can be produced at Belle II in a variety of production mechanisms



- Ability to reconstruct all neutral and charged FS particles gives Belle II a unique opportunity to search for exotic states

10 “exotic" candidates (not explained in conventional quark model), nature of 8 states under investigation, 17 consistent with quark model
All measurements provide critical insights for QCD

Unique studies in nuclear physics

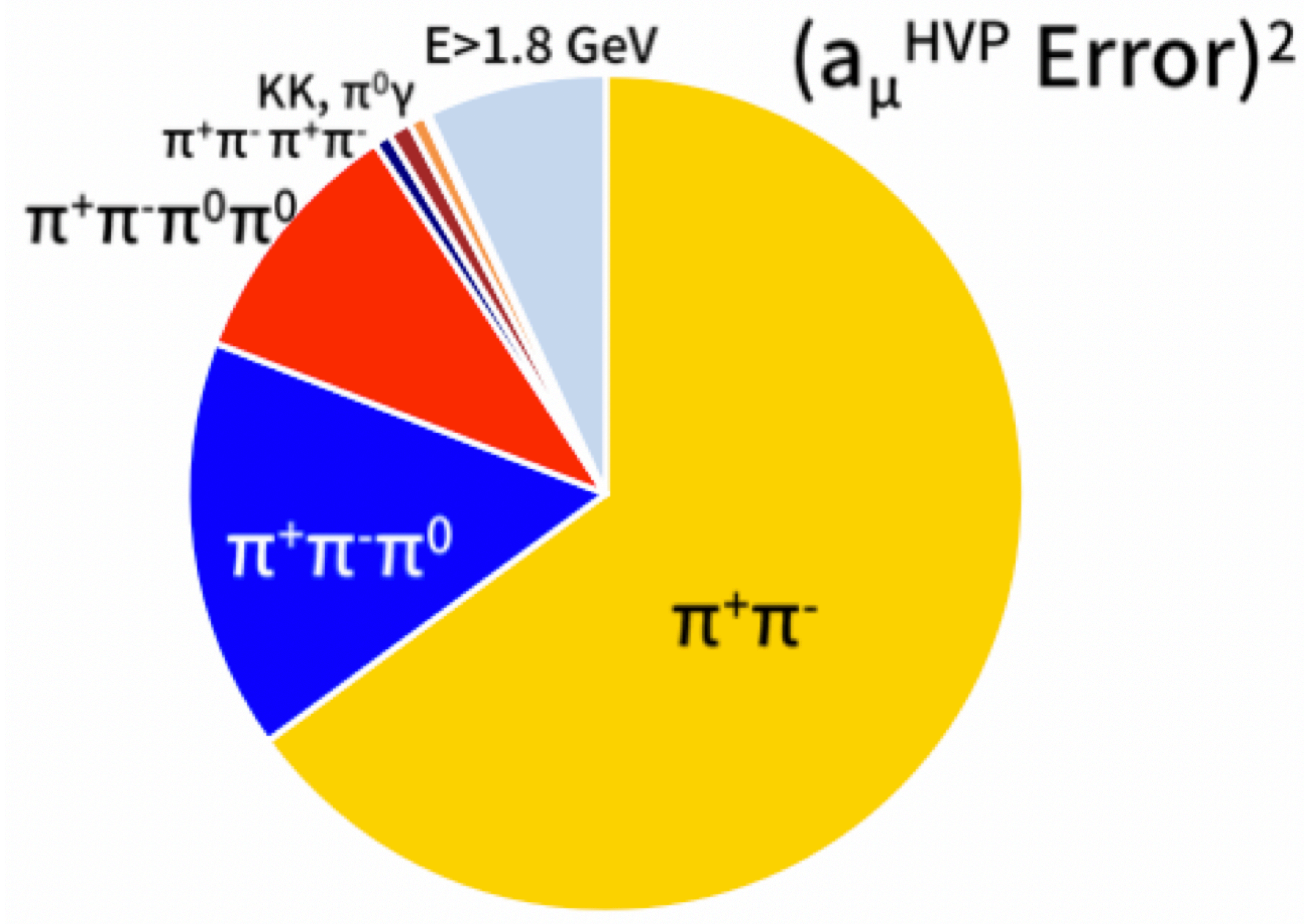
- Di-hadron spin-momentum correlation measurements at B factories: crucial input on nucleon partonic structure
- Precision data from Belle II will enable the extension to multi-dimensional correlations of spin and momenta
    - Important input to design/implementation at future electron-ion collider

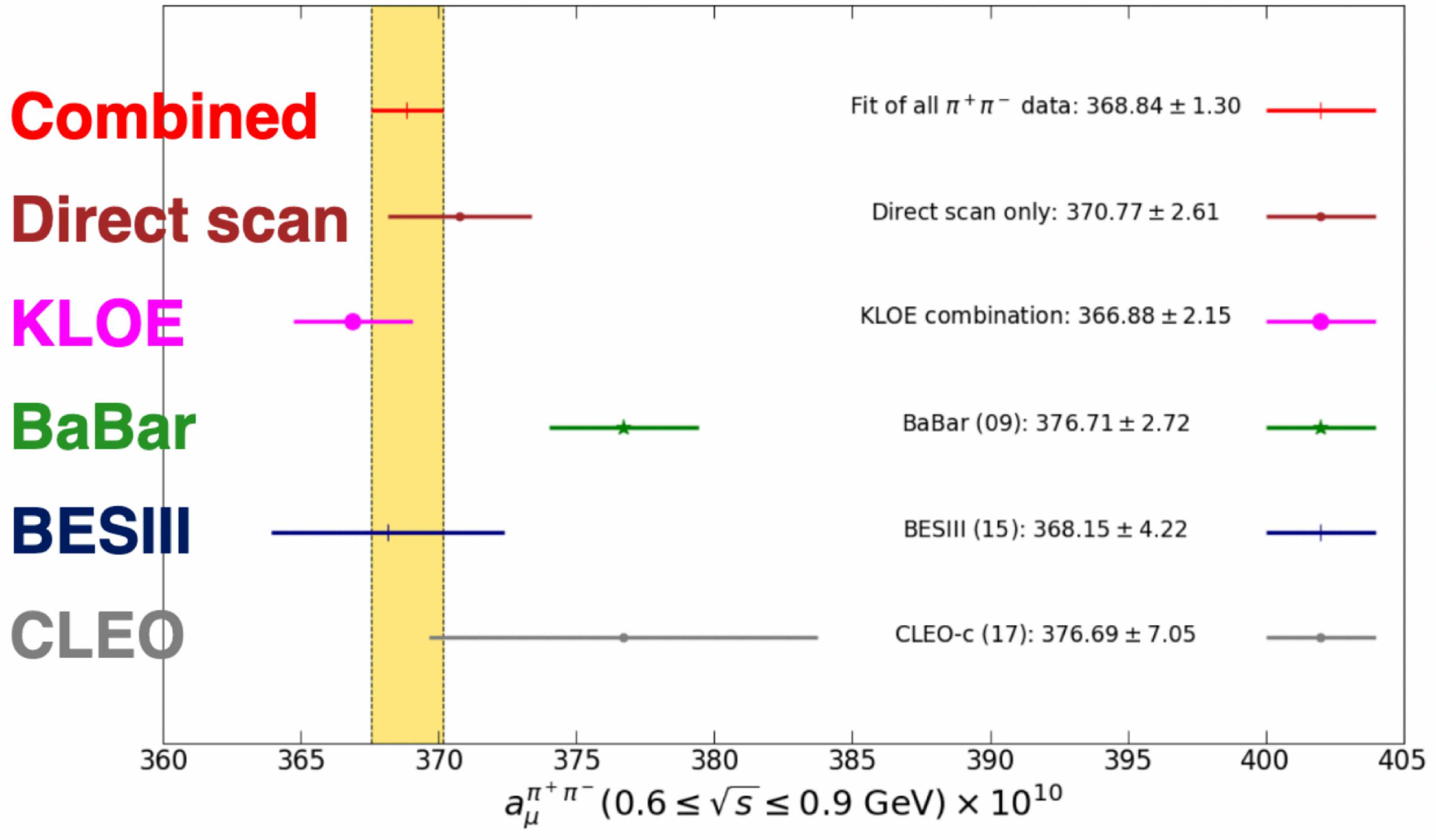
Snowmass paper: https://arxiv.org/abs/2204.02280

Belle II contributions to g-2 puzzle

Precise cross section measurements with high statistics data

- Belle II well positioned to constrain HVP in intermediate energy region where lattice/e^+e^- data disagree
- Current Belle II analysis aims for relative experimental uncertainty:
  - $\pi^+\pi^-$ channel about 0.5%
  - $\pi^+\pi^-\pi^0$ channel about 2%
    - Competitive with world data
    - Resolve KLOE/BaBar tension
    - Future improvements possible due to much larger dataset, PID
- Additional channels
  - $KK\pi^0\gamma$; $\gamma\gamma^* \rightarrow \pi^0$ (HLbL)
- Future opportunities
  - Conserved vector current (CVC): $\tau \rightarrow \pi^0\pi\nu_\tau \leftrightarrow e^+e^- \rightarrow \pi\pi$
    - Needs better understanding of isospin breaking effects





A. Keshavarzi, D. Nomura, and T. Teubner, Phys. Rev. D101, 014029 (2020)